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# BUILDING
# MATERIALS AND STRUCTURES

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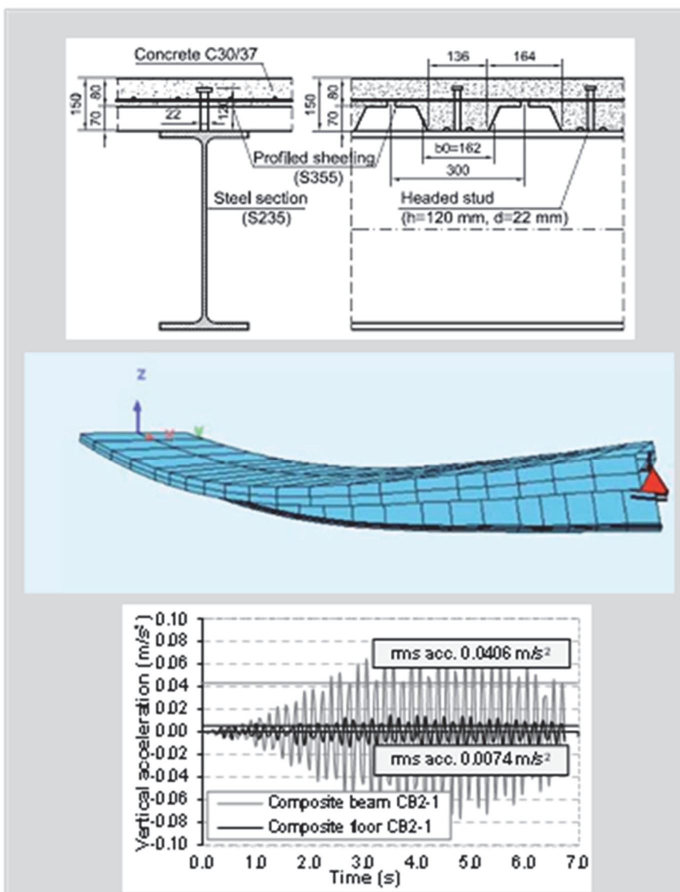

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**Aims and scope**

Building Materials and Structures aims at providing an international forum for communication and dissemination of innovative research and application in the field of building materials and structures. Journal publishes papers on the characterization of building materials properties, their technologies and modeling. In the area of structural engineering Journal publishes papers dealing with new developments in application of structural mechanics principles and digital technologies for the analysis and design of structures, as well as on the application and skillful use of novel building materials and technologies.

The scope of Building Materials and Structures encompasses, but is not restricted to, the following areas: conventional and non-conventional building materials, recycled materials, smart materials such as nanomaterials and bio-inspired materials, infrastructure engineering, earthquake engineering, wind engineering, fire engineering, blast engineering, structural reliability and integrity, life cycle assessment, structural optimization, structural health monitoring, digital design methods, data-driven analysis methods, experimental methods, performance-based design, innovative construction technologies, and value engineering.


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# EDITORIAL

Since the beginning of 2021 the Building Materials and Structures Journal has new Editor-in-Chief and Editorial Board as well as two new publishers.

Namely, new publishers of the Journal are Faculty of Civil Engineering (FCE) of Belgrade's University and Association of Structural Engineers of Serbia (ASES), together with the former publisher Society for Materials and Structures Testing of Serbia (SMSTS, in Serbian DIMK). New Journal's Editor-in-Chief is Professor Snežana Marinković from the FCE and new Editorial Board is constituted. This is an opportunity to express an appreciation to the previous Editor-in-Chief, Professor Radomir Folić, and members of the Editorial Board on their valuable contribution to the Journal's quality and promotion.

Following the modern society ever-growing demands the field of building materials and structures is continuously developing. Besides fulfilling the strength, serviceability, durability, economy, and aesthetic requirements modern structures should be robust, should provide protection against the accidents and various hazards, and should be sustainable. The environmental impact of the construction industry is significant and cannot be ignored if we are seeking for the protection and conservation of the Planet's environment. The pressure is on all engineers, architects and contractors to optimize use of new materials and novel technologies.

The aim of this Journal is to disseminate the innovative and original research and development in the field of **building materials** and **structures** and to promote its application in civil engineering projects. We are committed to maintaining the highest level of scientific and professional integrity in the published content. At the same time, we are encouraging researchers to publish their research and professionals to present novel technologies applied in projects already executed or under execution, as a path towards higher Journal visibility and indexing in Web of Science.

This issue contains several contributions regarding design and application of green building materials as well as actual problems in vibration analysis and design of steel-concrete composite floors due to pedestrian traffic. Also, a work on a historical development of Serbian research and science after World War II is selected for publication as a way of remembering the old and incentive for the new.

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**Review Paper**

# Harvest residues ash as a pozzolanic additive for engineering applications: a review and the catalogue

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***ABSTRACT***

Biomass ashes originating from wood and harvest residues combustion may be considered as one of the prospective environmentally friendly candidates for supplementary cementitious materials (SCM) production. In the region of Vojvodina province, biomass waste is becoming increasingly important as ''green'' fuel, thus allowing the reduction of the environmental impact of waste disposal, lowering the expensive fossil fuels application and its subsequent greenhouse gasses emission. In the light of the above, the present paper surveys the experimental studies of harvest residues ash (HRA) as a pozzolanic additive for engineering applications. Thus far conducted research on the HRA possible application in cementitious systems, worldwide and in the studied region, has been summarized and the benefits of such approaches outlined. Finally, locally available types of wheat straw, soya straw, sunflower husk, silo waste, oil rapeseed - based ashes were collected, characterized both physically and chemically, evaluated and presented through catalogue. The reactivity results, depending on the amorphous silica content and the achieved level of fineness, are very promising in terms of the potential reuse of these ashes in cementing systems.

## 1 Introduction: biomass as res

Using biomass to provide energy services is one of the most versatile options for increasing the share of renewable energy in the global energy system. Biomass for energy production may be obtained from a diverse range of sources, the most important of which are energy crops, agricultural and forestry residues, wastes, and existing forestry. There is a wide dispute about the most important factors affecting the contribution biomass might make to primary energy supply. These include the availability of arable land (agricultural land may be expanded at the expense of forested areas; or lost due to soil degradation or urbanization etc.), the productivity of the biomass grown on the land (climate change) and competition for alternate uses of the land (waste landfilling).

On the other hand, some scenarios assume that increases in food demand will primarily be met through increases in crop yields, which should be particularly required in developing countries. Forecasting models indicate that developing countries will account for most of the rapid urban population increase by 2050, hence the percentage of global energy used in cities is expected to increase considerably. Although cities continue to use fossil fuels as the main source of energy, biomass acts for a growing renewable energy source (RES) with high growth potential, due to its wide availability as a by-product of many industrial and agricultural processes.

As previously mentioned, the global economy is primarily based on fossil fuels to produce electricity, heat, fuels and energy, whereas they account for 81% of the total primary energy supply; nuclear energy produce 5% and RES 14% (of which the contribution of biomass is about 70%) [1]. The use of RES in the EU has grown from 13.2% in 2010 to 18.0% in 2018 [2]. Biomass is today used primarily for: 1) feed, 2) food and 3) energy, fuels and chemical feedstock production and, based on its availability and ever increasing demands, could act as an alternative to fossil resources by its conversion into food, feed, and bioenergy. Despite the large consumption of biomass as an energy source, enormous quantities remain in landfills as unused waste/raw materials.

Biomass-based materials are characterized by lower emissions of greenhouse gases than those from non-renewable sources, such as oil and coal. Combustion of biomass results in pollutant emissions, but not as much as in case of fossil fuels. Therefore, an increase in biomass

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renewable energy consumption reduces $CO_2$ emissions and cuts the demand for fossil fuels and their associated greenhouse gases (GHG) emission.

The potential of Serbia in RES is estimated at 6 million tons per year, whereas biomass accounts for 64%, i.e. 3.3 million tons annually. In the structure of planned primary energy production in Serbia for 2014, RES participated with 1,819 million tons per year, which accounted for about 17% of domestic primary energy production. In this, the highest share had solid biomass - 58%. Greatest potential of biomass in Serbia lies in the agricultural residue and wood biomass, a total of about 2.7 million tons (1.7 million tons in the remains of agricultural production and about 1 million tons in wood biomass) [3]. The utilization possibility of biomass as a fuel can be evaluated through its low thermal power - Table 1. Apart from these two sources of biomass, further major source is the residue of livestock production. Another group of biomass sources includes energy plants (e.g. miscanthus, fast-growing poplar and the like), and plants that serve as raw material for biodiesel and bioethanol (rapeseed, sunflower, corn, etc.).

It is estimated that the total potential of biomass from agriculture in Serbia is about 12.5 million tons per year. In 2019, the share of crop production in the total value of agricultural production equaled 66.0%, and that of livestock production equaled 34,0% [6]. When compared to 2018 the net index of physical volume of agricultural production decreased by 1,2%. There are many small individual landowners in Serbia, who deal with production of cereals or industrial plants, like sunflower or soya. A lot of crop farming production, almost 75% is achieved in small or medium size private ownership, while only about 25% of crop farming production belongs to agricultural companies of relatively larger size [7]. It is estimated that about half of harvest residues at large agricultural farms can be used for energy purposes, while only about 20% harvest residues, generated on relatively small private farms, can be used for energy purposes. Total quantities of harvested crops in Serbia for the period 2015-2019 are listed in Table 2.

*Table 1 - The energy potential of biomass production [4], [5]*

| Agricultural biomass | Low thermal power (MJ/kg) | Woody biomass | | Low thermal power (MJ/kg) | Other fuels | Low thermal power (MJ/kg) |
|---|---|---|---|---|---|---|
| Wheat straw | 14,4 | Beech | bark | 18,0 | Brown coal | 22,5 |
| Barley straw | 14,2 | | wood | 18,8 | Charcoal | 28,8 |
| Oat straw | 14,5 | Oak | bark | 19,7 | Light fuel oil | 42,1 |
| Rye straw | 14 | | wood | 18,4 | Light fuel oil | 41,8 |
| Corn | 13,5 | Spruce | bark | 21,2 | Petrol | 42,0 |
| Sunflower stem | 14,5 | | wood | 19,7 | | |
| Sunflower shell | 17,55 | Fir | bark | 21,0 | | |
| Soya straw | 15,7 | | wood | 19,5 | | |
| Rapeseed straw | 17,4 | Pine | bark | 20,6 | | |
| Stalks of tobacco | 13,85 | | wood | 21,2 | | |

*Table 2 - Harvested crops in Serbia for the period 2015-2019 [6]*

| Crop | Harvested quantity (in tons) per year | | | | |
|---|---|---|---|---|---|
| | 2015. | 2016. | 2017. | 2018. | 2019. |
| Wheat | 2 428 203 | 2 884 538 | 2 275 623 | 2 941 601 | 2 534 643 |
| Maize | 5 454 841 | 7 376 737 | 4 018 370 | 6 964 770 | 7 344 542 |
| Soya | 454 431 | 576 446 | 461 272 | 645 607 | 700 502 |
| Sunflower | 437 084 | 621 127 | 540 590 | 733 706 | 729 079 |
| Rapeseed | 33 402 | 39 404 | 48 740 | 135 422 | 84 311 |
| Tobacco | 8 776 | 7 811 | 7 173 | 7 169 | 7 992 |
| Sugar beet | 2 183 194 | 2 683 859 | 2 513 495 | 2 325 303 | 2 305 316 |
| *Total* | *10 999 931* | *14 189 922* | *9 865 263* | *13 753 578* | *13 706 385* |

*Table 3 - Main indicators of forestry in Serbia, 2015-2019 [6]*

| | Total forest exploitation Felled wood stock, gross volume, thousand $m^3$ | Regular artificial forestation, ha | | |
|---|---|---|---|---|
| | | Total | Conifers | Broadleaved |
| 2015 | 2928 | 1736 | 668 | 1068 |
| 2016 | 3134 | 1280 | 585 | 695 |
| 2017 | 3192 | 1984 | 654 | 1330 |
| 2018 | 3220 | 1547 | 694 | 853 |
| 2019 | 3313 | 3077 | 604 | 2473 |

The total area of forests in the Republic of Serbia extends over 2 237 511 ha. The state sector holds 963 458 ha, which is about 43% of the total forested area, and the remaining 57% is in private ownership. When compared to 2018, in 2019 artificial afforestation increased for 1 530 ha, which presents a growth of about 199%. The total area that was afforested in 2019 extended over 3 077 ha - Table 3 [6]. Woody biomass, especially wood pellets, is increasingly used for heating and power production and in light of relatively low external costs to reduce GHG emissions.

The main processes generating the energy obtained from biomass, both agricultural and woody, include direct combustion, pyrolysis, gasification, hydro gasification, liquefaction, alcoholic fermentation etc. Large amounts of biomass ashes are produced as waste products within these processes. They are most commonly disposed of in landfills or recycled on agricultural fields. Considering that the disposal costs of waste materials are ever-increasing, a sustainable ash management has to be established.

Globally, the imposing number of studies has successfully proved the viability of employing biomass ashes, such as: rice husk ash, wood ash, corn cob ash, as pozzolanic admixtures in cement composites, and have consequently encouraged the utilisation of blended cements with biomass waste, moving towards the utilization of more sustainable construction materials. Most of the studies on different types of harvest residues ashes (HRA) or wood ashes (WA) are carried by supplementing and adding as an additive in the place of binding material and/or fine aggregate and observed different changes in the properties because of influence of the pozzolana action.

The use of biomass ashes as building materials in engineering practice in Serbia has been scarcely investigated so far. Previous studies, conducted mostly on cement mortars blended with HRA [8,9,10,11], have documented that mortars, blended with wheat straw ash and soya straw ash, show a promising performance in strength, depending on the level of fineness and chemical composition of these ashes. However, very few studies have dealt with the reactivity and pozzolanic properties of other other available biomass ashes in Serbia.

Therefore, the present study is to give a brief review on the usage of different HRA, both globally and in Serbia, based on the type of the ash. In addition, locally available waste materials, originating from agriculture in Serbia, are explored and systematically presented through catalogue for possible SCM application for the first time.

## 2 Literature review on the application of different biomass ashes

The properties of biomass ashes, generated by biomass combustion, vary widely and heavily depend on: 1) biomass type; 2) combustion technology and temperature; 3) the location where the ashes are collected (fly ash, bottom furnace ash); 4) further treatment of the ashes (grinding processing). These contributing factors influence two major elements of potential biomass ashes application as SCMs: amorphous silica content and the level of fineness.

Below is a brief overview of the different types of biomass ashes used in the experimental research worldwide and the results obtained therein.

### 2.1 Rice husk ash

Rice husk ash (RHA) is a combustion by-product of grain husks of rice, as waste agricultural material. India is the world's second rice producer, immediately after China, with 104 million tons of rice produced annually. Annually, nearly 3.7 million tons of rice husks are produced. The rice husk contains about 50% cellulose, 25-30% lignin and 15-20% silicate gel. Several studies have been carried out to evaluate the feasibility of RHA. These studies have shown that

- RHA can be used as low cost building material, improving the durability of the cementitious system and producing high strength concrete [12];
- After combustion (the optimum combustion temperature for obtaining highly reactive RHA is 600°C), the ash is primarily composed of reactive silica and is characterized with high level of fineness [13];
- By using RHA, as replacement of part of the cement, consistency of fresh concrete is reduced due to the large specific surface area of the ash, hence a higher amount of water is required for concrete to maintain the same consistency. As a result of the reduced amount of cement and pozzolanic activity, the setting time is prolonged;
- Due to the filer effect (fine particles of RHA), a very dense structure is formed, with reduced permeability, decreased drying shrinkage and improved mechanical properties. Studies in which up to 20% of cement was replaced with RHA showed up to 89% lower permeability to penetration of chlorides. Also, RHA application, as a substitute for a part of cement in concrete, the frost resistance and the alkali-silicate reaction is shown to be

significantly increased [14]. Therefore, the usage of this type of ash contributes to the improved physical, mechanical and durability properties of cement composites.

## 2.2 Sugarcane bagasse ash

Sugarcane bagasse ash (SCBA) is an industrial by product produced in the sugar mills after the extraction of sugar from the sugarcane, whereas fibrous material (bagasse) is obtained. India, along with Brazil, is the largest sugarcane producer in the world. Approximately 380 million tons of sugar cane is produced annually in India, disposing a large amount of waste or ash, thereby. Optimum combustion temperature for obtaining highly reactive ash is estimated at 600-800°C [15]. Conducted studies revealed a favourable chemical composition of the ash in terms of its pozzolanic acitivity, primarily due to the high content of amorphous silica (≈78%) [16]. The authors summarized following observations regarding the properties and use of SCBA as SCM:

- The bulk density of SCBA is lesser than OPC; the volume occupied for a supposed mass will be higher, hence ash particles fill the small pores of concrete making it less permeable [17];
- Due to high level of fineness the concrete containing SCBA require higher amount of super-plasticizing as compared to the control mix to achieve the same workability [18];
- OPC replacement of 10% by weight of SCBA allows obtaining concrete with excellent mechanical performance and durability properties [19];
- The use of SCBA is efficient in the production of self-compacting concrete [20].

## 2.3 Palm oil fuel ash

Palm oil fuel ash (POFA) is a waste material resulting from the combustion of palm fibres and leaves for the generation of electricity. Currently, in Malaysia, oil palm plantations spread over three million hectares of land, whereby more than 15 million tons of palm oil is produced annually, generating 2.6 million tons of ash, thereby. Uncontrolled disposal of this type of ash occupies valuable land, but also leads to pollution of the environment and disruption of human health. The summarized knowledge on the applications of the ash in engineering practise includes:

- The appropriate fineness could be achieved by using a grinding mill;
- Due to a relatively high content of silica (55-65%), it can be extremely reactive, depending on the adjusted level of fineness [21];
- Along with ordinary pozzolanic materials, POFA reduces the consistency, lowers the heat of the hydration and prolongs the setting time of the concrete;
- Most of the researchers obtained the compressive strength of concrete containing 10–30% POFA higher than that of control concrete [22]. The early age increase is attributed to the filler effect of the fine ash particles, while at the later stages; the subsequent formation of C-S-H products improves the interfacial bonding between the pastes and the aggregates and thus increases the strength.

## 2.4 Corn cob ash

Over 500 million tons of corn is produced annually in the world. The United States is the largest producer of corn with 43%, followed by Africa with 7%. There is a significant opportunity to burn the waste parts of corn plant (cobs and stover) after harvest, and use the ash as a potential cement replacement. A review of the literature shows mixed results regarding the inclusion of corn cob ash (CCA) in concrete:

- CCA contains more than 65% reactive silica [23],
- Many researchers reported a significant reduction in the compressive strength as a result of replacing OPC with CCA [24, 25];
- Concrete incorporating CCA exhibits lower water absorption and shows better resistance to sulphate attack compared to the reference concrete [26];
- Authors outline mixed results regarding the influence of CCA on the fresh properties of concrete, as well. Some reported the reduced concrete slump with the addition of CCA, while others found that CCA increases the concrete slump.

The mixed results can be connected with a variety of factors, such as: the use of different watering regimens (irrigated vs. non-irrigated corn), type of fertilizer, and the species of corn, in addition to aforementioned indicators.

## 2.5 Wheat straw ash

Wheat is one of the primary sources of food. The current utilization of wheat straw is associated with energy source, pulp and paper, nano-materials, bioethanol, fertilizer, additive for mud houses. Considerable amounts of wheat straw ash (WSA), which has been investigated to a small extent as a potential pozzolanic material, are generated in the process of straw combustion. According to the literature results on the reactivity and possible WSA application in cementitious systems, following observations were noted:

- The chemical composition of WSA (obtained in Serbia) is characterized by high alkali content (20%) and significant amorphous silica content (52%) [27];
- Mechanical processing, such as grinding in lab ball mill, could significantly reduce the particle size, increase the level of fineness and amplify the amorphousness of WSA [28];
- WSA fulfills criteria for pozzolanic materials, including: activity index, setting time and soundness of powder fly ash materials, given in EN 450-1 [29];
- Optimum cement replacement level, determined by [29], was estimated at 15%, whereas the mortar containing 15% WSA has shown comparable strength to that of control mortar at 7 days, and even higher strength at ages of 28 and 91 days, respectively. Similar trend was registered by Dehane et al. [30]. At the age of 28 days, the strength of the mortar with 12,5% WSA exceeded the strength of the reference mortar, and this difference, due to the pozzolanic reaction, increased over time. This mortar was characterized by a smaller water absorption compared to the absorption of the OPC mortar at the age of 28 days (due to the filler effect of small WSA particles);
- Optimum cement replacement level with WSA in cement mortars is determined to be 30%, without any adverse effect on its mechanical properties [9].

### 2.6 Other biomass ashes

Few researchers have provided the information on far less utilized biomass ashes, such as: oyster shells ash [31], groundnut shells ash [32], bamboo leaf ash [33], sunflower stalk ash [34], sunflower husk ash [35], mischantus ash [36], barley ash [37], olive husk ash [35], coconut shell ash [38], rape straw ash [39] and eucalyptus biomass ash [40].

The major factor for the valorization of biomass ashes lies in the fact that they contain high amounts of reactive silica, which makes them suitable as cement substitutes. Silica content of different types of biomass ashes, used as cement substitutes worldwide, as well as recommended replacement level, by authors, is given in Table 4.

## 3 Harves residues ash - potential in APV, Serbia

The first step in preparing catalogue of available biomass ashes is to summarize collected information. In the region, which is involved in the research (Bačka, Srem and Mačva), within the realization of the project IPA Interreg ECO Build, cooperation was established with eleven companies that use harvest residues as an energy source for obtaining heat energy. A brief overview of the available types and quantities of generated biomass ashes in AP Vojvodina is presented in Table 5. Samples of biomass ashes were taken and basic data on generated ashes were collected, including:

- types of used biomass,
- combustion technology,
- achieved combustion temperatures in boiler furnace,
- generated quantities of biomass ash per year,
- disposal of biomass ash, as generated by-product.

Based on the gathered information, most of the harvest residues ashes produced are either disposed of in landfill or recycled on agricultural fields or forest, while the companies which combust biomass pay considerable price for the transportation and landfilling of these ashes.

*Table 4 - Silica content and recommended cement replacement level of various biomass ashes*

| | Silica content (%) | Reference | Recommended cement replacement level |
|---|---|---|---|
| Rice husk ash (RHA) | 80-95 | Siddika et al. [41] | 30% |
| Corn cob ash (CCA) | 60-70 | Adesanya et al. [42] | 10% |
| Wheat straw ash (WSA) | 50-70 | Šupić et al. [9] | 30% |
| Palm oil fuel ash (POFA) | 55-80 | Thomas et al. [22] | 20% |
| Sugar cane straw ash (SCSA) | 35 | Khalil. et al. [19] | 20% |
| Sunflower stalk ash (SSA) | 25 | Aksogˇan O. et al. [43] | 10% |
| Bamboo leaf ash (BLA) | 75-85 | Cociñaa E.V. et al. [44] | 20% |
| Groundnut shell ash (GSA) | 40-50 | Alaneme K.K. et al. [45] | 8% |
| Oyster shell ash (OSA) | 5 | Gengying Li et al. [46] | more research necessary |
| Miscanthus ash (MA) | 50-60 | Wigley F. et al. [47] | more research necessary |
| Barley husk ash (BHA) | 70-80 | Khalil et al. [48] | 20% |
| Sunflower husk ash (SHA) | 30-60 | Demirbas A. et al. [49] | 15% |
| Olive stone (pit) ash (OSA) | 5 | Font et al. [50] | more research necessary |
| Coconut shell ash (CSA) | 65 | Opeyemi J. et al. [51] | more research necessary |
| Rape straw ash (RSA) | 35 | Masiá T.A.A. et al. [52] | more research necessary |
| Eucalyptus biomass ash (EBA) | 1-5 | Teixeira A.H.C. [53] | more research necessary |

*Table 5 - Available quantities of biomass ashes in AP Vojvodina*

| Company | Biomass type | Temperature of combustion | Types of biomass ashes | Produced quantities of ash per year (tons) |
|---|---|---|---|---|
| Mitrosrem Sremska Mitrovica | wheat straw<br>soya straw | 600-650°C | 1. ash from boiler furnace<br>2. ash from multiciklon<br>3. fly biomass ash | 15 |
| Soya Protein Bečej | wheat straw<br>soya straw<br>silo waste<br>melasa | 700-900°C | 1. ash from boiler furnace<br>2. ash from multiciklon<br>3. fly biomass ash | 1100 |
| The Veterinary Institute Subotica | agro pellets of wheat straw and soya straw | 450-550°C | 1. ash from boiler furnace<br>2. ash from multiciklon<br>3. fly biomass ash | 240 |
| Hipol Odžaci | agro pellets of soya straw | 800-1000°C | 1. ash from boiler furnace<br>2. ash from multiciklon<br>3. fly biomass ash | 700 |
| Victoria Starch Zrenjanin | agro pellets of wheat straw and soya straw | unknown | 1. ash from boiler furnace | 9 |
| Almex-IPOK Zrenjanin | agro pellets of wheat straw and soya straw<br>sunflower husk | 700-900°C | 1. ash from boiler furnace<br>2. ash from multiciklon<br>3. fly biomass ash | 1100 |
| KNOT-AUTOFLEX Bečej | wheat straw<br>soya straw | unknown | 1. ash from boiler furnace | 60 |
| Fishery Lovćenac | soya straw | unknown | 1. ash from boiler furnace<br>2. ash from multiciklon | 9 |
| Victoria Oil Šid | sunflower husk | 700-1000°C | 1. ash from boiler furnace<br>2. ash from multiciklon | 720 |
| Sava Kovačević Vrbas | cob corn | 500°C | 1. ash from boiler furnace | 30 |
| PTK Panonija Mecker farm | wheat straw<br>soya straw | 500°C | 1. ash from boiler furnace | 60 |
| | | | Total | **≈ 5.000 tons** |

## 4 Properties and catalogue of harvest residues ashes in APV Vojvodina

### 4.1 Materials and Methods

#### 4.1.1 Materials

***Cement***

Ordinary Portland cement (OPC), originating from Lafarge cement factory in Beočin, Serbia, was used. The cement has a specific gravity of 3.1 g/cm$^3$ and the Blaine fineness of 4.000 cm$^2$/g.

***Biomass ashes***

For experimental investigation of chemical and physical properties and pozzolanic activity of biomass ashes, the following materials were collected and tested:

- Wheat straw ash (WSA), "Mitrosrem" Sremska Mitrovica,
- Mixed wheat and soya straw ash (WSSA-1), „Soya-protein" Bečej,
- Mixed wheat and soya straw ash (WSSA-2), „IPOK" Zrenjanin,
- Soya straw ash (SSA), „HIPOL" Odžaci,
- Silo waste ash (SWA), „Soya-protein" Bečej,
- Oil rapeseed ash (ORA), „Knot-Autoflex" Bečej,
- Mixed wheat straw and sunflower husk ash (WSSHA), „Soya-protein" Bečej,
- Sunflower husk ash (SHA), „Victoria Oil" Šid.

The ashes were roughly sieved (apart from SHA), through a 4mm sieve, in order to separate un-burnt straw and other large impurities. In order to obtain a material with satisfactory specific surface area, ashes were further ground in a laboratory ball mill for 6h.

#### 4.1.2 Methods

The chemical composition of collected ashes was determined using energy dispersive X-ray fluorescence spectrometer (EDXRF 2000 Oxford instruments) according to EN 196-2, 2015 and ISO 29581-2, 2010. The representative samples (100 g) were pulverized in a laboratory vibratory mill prior to the testing. The loss on ignition (LOI) was determined as a weight difference between 20 °C and 950 °C.

Specific surface area of biomass ashes was determined according to Blaine air permeability method given in EN 196-6, 2011, which is widely used for the fineness determination of hydraulic cement. The test is based on the principle of resistance to air flow through a partially compacted sample of powder material.

Soundness of biomass ashes was determined in accordance with EN 196-3, 2010. The method is used for assessing whether this physical property of a SCM material is in conformity with the requirements given in EN 450-1.

The pozzolanic activity was studied on samples prepared according to the procedure given in SRPS B.C1.018, 2015. Mortars were prepared with biomass ash, slaked lime and standard sand, with the following mass proportions: $m_{sl}$:$m_{bash}$:$m_{qs}$=1:2:9 and water – binder ratio 0.6 (where: $m_{sl}$ – mass of slaked lime; $m_{bash}$ – mass of biomass ash; $m_{qs}$ – mass of CEN standard sand). After compacting, the samples were hermetically sealed and cured for 24 h at 20 °C, then for 5 days at 55 °C. Subsequently, 24h period was allowed for samples cooling process to reach 20 °C, followed by compressive and flexural strength tests.

The activity index of biomass ashes was examined according to EN 450-1, 2014. Activity index is defined as a ratio (in percent) of the compressive strength of mortar prepared with 75% test cement plus 25% ash by mass, and the compressive strength of standard cement mortar, when tested at the same age. The preparation of mortar test specimens and determination of the compressive strength were carried out in accordance with EN 196-1, 2018.

### 4.2 Chemical composition

The chemical compositions of OPC and selected biomass ashes are given in Table 6. Obtained chemical composition of pure WSA indicates the relatively high participation of major oxides $SiO_2$+$Al_2O_3$+$Fe_2O_3$ (≈70%), as well as reactive silica (67%).

*Table 6. Chemical composition of OPC and biomass ashes*

| Material (%) | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | $SO_3$ | $P_2O_5$ | LOI | $SiO_2$+ $Al_2O_3$+ $Fe_2O_3$ | Reactive $SiO_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Cement** | 21.25 | 5.55 | 25.3 | 61.6 | 2.37 | 0.25 | 0.72 | 3,75 | - | 1.77 | **52,1** | **-** |
| **WSA** | 69.13 | 1.12 | 0.73 | 5.78 | 2.50 | 0.11 | 13.03 | 0.20 | 1.72 | 5.18 | **70,98** | **67** |
| **WSSA-1** | 56.36 | 2.03 | 1.53 | 7.13 | 3.54 | 0.20 | 20.02 | 0.18 | 3.72 | 4.85 | **59,92** | **41** |
| **WSSA-2** | 54.01 | 3.51 | 2.06 | 8.09 | 3.22 | 0.27 | 19.16 | 0.38 | 1.26 | 7.72 | **59,58** | **44** |
| **SSA** | 32.62 | 4.58 | 1.46 | 15.78 | 8.33 | 0.85 | 20.96 | 0.47 | 3.72 | 10.73 | **38,66** | **25** |
| **SWA** | 43.66 | 5.41 | 2.06 | 15.89 | 5.05 | 0.97 | 14.09 | 0.76 | 4.82 | 6.41 | **51,13** | **25** |
| **ORA** | 32.37 | 6.32 | 2.45 | 14.00 | 2.91 | 0.89 | 17.85 | 3.78 | 1.44 | 17.61 | **41,14** | **15** |
| **WSSHA** | 44.12 | 1.99 | 1.93 | 10.94 | 4.91 | 0.26 | 16.24 | 0.45 | 5.43 | 13.05 | **48,04** | **35** |
| **SHA** | 5.34 | 1.19 | 1.03 | 12.96 | 9.94 | 0.68 | 44.76 | 9.71 | - | 12.64 | **7,56** | **5** |

## 5 Catalogue of harvest residues ashes in APV Vojvodina

After biomass ashes preparation (sieving, grinding), along with determination of chemical composition test, the following testing were conducted for the purpose of catalogue creation:

- Specific gravity,
- Blaine fineness,
- Soundness,
- The pozzolanic activity,
- The activity index.

The obtained results of listed HRA properties are presented through the catalogue, given below.

Based on the results of an own experimental research [7-11,54-55], as well as the conclusions the other authors derived [43,49,52,56], a possible cement replacement level with tested types of HRA was estimated for their application in mortar and concrete. These values are also showed in the catalogue.

Considering the high amount of water-soluble potassium oxide in sunflower husk ash, this type of ash can be potentially utilized as the alkali solution for the activation of silica and alumina rich precursor and the production of alkali activated materials. However, more research regarding this assumption is inescapable.

### 5.1 Wheat straw ash: basic properties and possible application

***Wheat straw ash**, before sieving and grinding*

***Wheat straw ash**, after sieving and grinding*

| | |
|---|---|
| *Ash origin* | Mitrosrem, Veliki Radinci |
| *Basic data on the ash* | Bottom ash, roughly sieved through a 4mm sieve |
| *Available amount per year* | 15 tons |
| *Reactive silica content* | 67% |
| *Specific gravity* | 2380 kg/m$^3$ |
| *Blaine fineness* | 950 m$^2$/kg |
| *Soundness* | satisfactory |
| *The pozzolanic activity* | Class 10 |
| *The activity index* | $I_{28}$=104%<br>$I_{90}$=108% |
| *Recommended cement replacement level in mortar* | up to 50% (from the aspect of achieved mechanical properties of concrete) |
| *Recommended cement replacement level in concrete* | up to 50% (from the aspect of achieved mechanical properties of mortar) |

## 5.2 Mixed wheat and soya straw ash: basic properties and possible application

***Mixed wheat and soya straw ash**, before sieving and grinding*

***Mixed wheat and soya straw ash**, after sieving and grinding*

| | |
|---|---|
| *Ash origin* | Soja Protein, Bečej |
| *Basic data on the ash* | Bottom ash, roughly sieved through a 4mm sieve |
| *Available amount per year* | 300-1100 tons |
| *Reactive silica content* | 41% |
| *Specific gravity* | 2370 kg/m$^3$ |
| *Blaine fineness* | 1550 m$^2$/kg |
| *Soundness* | satisfactory |
| *The pozzolanic activity* | Class 5 |
| *The activity index* | $I_{28}$=92%<br>$I_{90}$=92% |
| *Recommended cement replacement level in mortar* | up to 30% (from the aspect of achieved mechanical properties of concrete) |
| *Recommended cement replacement level in concrete* | up to 30% (from the aspect of achieved mechanical properties of mortar) |

5.3 Mixed wheat and soya straw ash: basic properties and possible application

***Mixed wheat and soya straw ash**, before sieving and grinding*

***Mixed wheat and soya straw ash**, after sieving and grinding*

| | |
|---|---|
| *Ash origin* | IPOK, Zrenjanin |
| *Basic data on the ash* | Bottom ash, roughly sieved through a 4mm sieve |
| *Available amount per year* | 1100 tons |
| *Reactive silica content* | 44% |
| *Specific gravity* | 2380 kg/m$^3$ |
| *Blaine fineness* | 610 m$^2$/kg |
| *Soundness* | satisfactory |
| *The pozzolanic activity* | Class 10 |
| *The activity index* | $I_{28}$=95%<br>$I_{90}$=102% |
| *Recommended cement replacement level in mortar* | up to 50% (from the aspect of achieved mechanical properties of concrete) |
| *Recommended cement replacement level in concrete* | up to 50% (from the aspect of achieved mechanical properties of mortar) |

### 5.4 Soya straw ash: basic properties and possible application

***Soya straw ash**, before sieving and grinding*

***Soya straw ash**, after sieving and grinding*

| | |
|---|---|
| *Ash origin* | Hipol, Odžaci |
| *Basic data on the ash* | Bottom ash, roughly sieved through a 4mm sieve |
| *Available amount per year* | 700 tons |
| *Reactive silica content* | 25% |
| *Specific gravity* | 2400 kg/m$^3$ |
| *Blaine fineness* | 520 m$^2$/kg |
| *Soundness* | satisfactory |
| *The pozzolanic activity* | Insufficient |
| *The activity index* | $I_{28}$=70%<br>$I_{90}$=69% |
| *Recommended cement replacement level in mortar* | up to 10% (from the aspect of achieved mechanical properties of concrete) |
| *Recommended cement replacement level in concrete* | up to 10% (from the aspect of achieved mechanical properties of mortar) |

5.5 Silo waste ash: basic properties and possible application

***Silo waste ash**, before sieving and grinding*

***Silo waste ash**, after sieving and grinding*

| | |
|---|---|
| *Ash origin* | Soja Protein, Bečej |
| *Basic data on the ash* | Bottom ash, roughly sieved through a 4mm sieve |
| *Available amount per year* | 300-1100 tons |
| *Reactive silica content* | 25% |
| *Specific gravity* | 2390 kg/m$^3$ |
| *Blaine fineness* | 1180 m$^2$/kg |
| *Soundness* | satisfactory |
| *The pozzolanic activity* | Class 5 |
| *The activity index* | $I_{28}$=90%<br>$I_{90}$=100% |
| *Recommended cement replacement level in mortar* | up to 30% (from the aspect of achieved mechanical properties of concrete) |
| *Recommended cement replacement level in concrete* | up to 30% (from the aspect of achieved mechanical properties of mortar) |

5.6 Oil rapeseed ash: basic properties and possible application

***Oil rapeseed ash****, before sieving and grinding*

***Oil rapeseed ash****, after sieving and grinding*

| | |
|---|---|
| *Ash origin* | Knot Autoflex, Bečej |
| *Basic data on the ash* | Bottom ash, roughly sieved through a 4mm sieve |
| *Available amount per year* | 60 tons |
| *Reactive silica content* | 15% |
| *Specific gravity* | 2320 kg/m$^3$ |
| *Blaine fineness* | 610 m$^2$/kg |
| *Soundness* | satisfactory |
| *The pozzolanic activity* | Insufficient |
| *The activity index* | $I_{28}$=86%<br>$I_{90}$=85% |
| *Recommended cement replacement level in mortar* | up to 30% (from the aspect of achieved mechanical properties of concrete) |
| *Recommended cement replacement level in concrete* | up to 30% (from the aspect of achieved mechanical properties of mortar) |

## 5.7 Mixed wheat straw and sunflower husk ash: basic properties and possible application

***Mixed wheat straw and sunflower husk ash**, before sieving and grinding*

***Mixed wheat straw and sunflower husk ash**, after sieving and grinding*

| | |
|---|---|
| *Ash origin* | Soja Protein, Bečej |
| *Basic data on the ash* | Bottom ash, roughly sieved through a 4mm sieve |
| *Available amount per year* | 300-1100 tons |
| *Reactive silica content* | 35% |
| *Specific gravity* | 2185 kg/m$^3$ |
| *Blaine fineness* | 1065 m$^2$/kg |
| *Soundness* | satisfactory |
| *The pozzolanic activity* | Insufficient |
| *The activity index* | $I_{28}$=76%<br>$I_{90}$=83% |
| *Recommended cement replacement level in mortar* | up to 30% (from the aspect of achieved mechanical properties of concrete) |
| *Recommended cement replacement level in concrete* | up to 30% (from the aspect of achieved mechanical properties of mortar) |

5.8 Sunflower husk ash: basic properties and possible application

***Sunflower husk ash*** *(grinding processing was not necessary)*

| | |
|---|---|
| *Ash origin* | Victoria Oil, Šid |
| *Basic data on the ash* | Fly ash |
| *Available amount per year* | 720 tons |
| *Reactive silica content* | 5% |
| *Specific gravity* | 2200 kg/m$^3$ |
| *Blaine fineness* | 610 m$^2$/kg |
| *Soundness* | satisfactory |
| *The pozzolanic activity* | Insufficient |
| *The activity index* | $I_{28}$=0<br>$I_{90}$=0 |
| *Recommended cement replacement level in mortar* | Not recommended as SCM |
| *Recommended cement replacement level in concrete* | Not recommended as SCM |

## 6 Conclusions and further research

The aim of this study was to collect and analyze the ashes originating from harvest residues combustion, locally available in Vojvodina. Novel and useful information on the characteristics of wheat straw, soya straw, sunflower husk, oil rapeseed and silo waste based ashes is presented through the catalogue, which is the first step in defining an environmentally friendly route for this type of waste, offering an opportunity for the creation of new sustainable cement-based composites, thereby. Experimental research of HRA as potentially building materials should result in guidelines relevant for their further use of as mineral/inert additives in cementitious systems. To achieve this goal, further investigations will include determination of HRA influence on basic properties of mortars, concretes and other composites. The results of such experimental research should verify the possibility to obtain biomass ash-based ECO composites with comparable or better physical and mechanical properties than those of the reference composites. As the catalogue demonstrated a high variability of HRA properties, other directions of the ashes application (construction of roads and embankments, alkali-activated materials, etc.) are also possible and up for research, depending on the type of the ash. These composites will be characterized by a lower consumption of cement, thus reducing the $CO_2$ emissions and meeting the principles of sustainable development.

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# Prediction models for high-volume fly ash concrete practical application: mechanical properties and experimental database

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fly ash efficiency,
compressive strength,
splitting tensile strength,
modulus of elasticity

***ABSTRACT***

The analysis of available experimental results of high-volume fly ash concrete mechanical properties showed that extensive amount of research had been done so far. However, a comprehensive analysis of basic high-volume fly ash concrete mechanical properties was not found in the literature. Having that in mind, the database of 440 high-volume fly ash concrete and 151 cement concrete mixtures collected from literature was made. The application of European Code EN 1992-1-1 prediction models for cement concrete mechanical properties, as well as existing proposals for high-volume fly ash concrete properties, were statistically evaluated on the results from the database. The analysis showed that the prediction models defined in EN 1992-1-1 for compressive strength, tensile strength and for modulus of elasticity can be used for high-volume fly ash concrete, in the given form or with modifications proposed in literature, with similar accuracy and variation of results as for cement concrete. Own model for fly ash efficiency prediction was developed.

## 1 Introduction

In the modern age, one of the main challenges on the path of preserving the environment is finding the solution for large amounts of waste or by-products generated by different industries. Recycling and reuse of these materials is currently widely investigated in order to prevent their further increase, and if possible, to reduce already generated amounts. The construction industry, and specifically its major part – concrete industry, is a potential beneficiary of this approach since large quantities of waste or by-products can be used in the production of concrete [1]. Different pozzolanic waste materials are already widely used as supplementary cementitious materials (CM) in concrete production making it more sustainable. Among them, coal fly ash (FA) is most commonly used in the production of concrete. FA is a by-product of the combustion of pulverized coal in thermal power plants. Depending on the type of coal and the production processes, FA consists of a different proportion of oxides—mostly silica, alumina and calcium—and can display pozzolanic activity. This enables it to be a substitution of cem[3]ent and fine aggregate in concrete..

If part of the cement (and eventually fine aggregate) in concrete mixture is replaced with FA, the consumption of natural aggregates and $CO_2$ emissions are reduced, which is clearly the environmental benefit [2]. The cement industry is responsible for more than 5% of the global $CO_2$ emissions in 2016, and the production rate of cement is expected to grow continuously at a rate of 10% annually to reach a historical maximum of around 5000 Mt/Year by 2021 [3], [4].

FA has been used in concrete since 1930s as a partial replacement of Portland cement to decrease the amount of early heat generation during the construction of dams. In the last few decades higher amounts of FA as a partial replacement of Portland cement or fine aggregate have been used. In 1985, the Advanced Concrete Technology Group at CANMENT, Canada, developed a high volume FA concrete (HVFAC) [5] with more than 50% of FA in total mass of CM. According to the progress in current research, the next couple of years would see the replacement of FA to a maximum of 60% by mass [6].

Up to now, a lot of research has been carried out regarding HVFAC mechanical properties. The behavior of hardened HVFAC depends upon many factors, but mostly upon FA fineness, chemical and mineralogical properties, cement type, water-to-CM mass (W/CM) ratio, amount of FA and cement etc. It can generally be concluded that HVFAC has lower compressive strength compared with the control

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cement concrete made with the same component materials only by partially replacing cement with FA [7]. Slower compressive strength development at early ages can be also noticed in HVFAC but greater increase at ages after 28 days compared with cement concrete [8]-[10].

Despite the fact that HVFAC has its disadvantages [6], [7], there is a great possibility for its practical application. Most industrial and commercial buildings require concrete with compressive strength of about 30 MPa in majority of their structural and non-structural elements. This compressive strength is easily achievable with HVFAC. Greater use of HVFAC in such applications could significantly reduce the amount of used cement and, therefore, the amount of emitted $CO_2$.

The use of HVFAC in concrete structures requires defined and standardized prediction models for mechanical properties which is not yet the case. So, the main aim of this work was to provide guidelines for practical HVFAC mix design procedure and prediction of basic mechanical properties.

However, chemical and physical properties of FA differ depending on the coal type, process methods etc. Concrete properties are affected by this FA chemical and physical heterogeneity [11] thus making general conclusions on the HVFAC ecological and economic efficiency rather unreliable. One possible way to bring this issue to a closure at the current state-of-the knowledge is to propose prediction models for HVFAC mechanical properties based on a comprehensive statistical analysis of the experimental research done so far. These models should be able to predict the basic HVFAC properties considering the FA amount and its chemical and physical heterogeneity, with a chosen reliability level. For that purpose, the database of available HVFAC experimental results from the literature was made. Firstly, the European standard EN 1992-1-1 [12] predictions for compressive strength, splitting tensile strength and modulus of elasticity of CC (cement concrete) were evaluated if they were applicable on the HVFAC mixtures from the database or new models or modifications were needed. Secondly, already proposed prediction models from literature were re-evaluated using statistical analysis on the HVFAC database and some own corrections were given.

## 2 Method

The analysis of experimental results of basic mechanical properties was done in two steps: (1) collection of studies with available experimental results and available information about component materials used for the production of FA concrete and (2) selection of results for further analysis based on selected criteria. The experimental results were collected from available research papers, technical reports, master and doctoral theses using content analysis. The first step was the systematic collection of all available studies on FA concrete that had own experimental results of basic mechanical properties. The search was done in the Scopus, Science Direct and Google Scholar databases, using the following key words: *fly ash, fly ash concrete, high-volume fly ash concrete, mechanical properties, compressive strength, modulus of elasticity, splitting tensile strength* and *experimental results*. Relevant studies with available experimental results found as references in previously found studies were also considered.

Further on, the selection of the results was done based on the following two criteria: only studies with class F FA were selected and the amount of FA in CM was chosen in the range between 40% and 75%. FA was classified as class F according to ASTM C618 [13] – minimum 70% of total FA mass consisted of $Al_2O_3$, $SiO_2$ and $Fe_2O_3$. If the selected study did not contain the FA classification, it was made based on the reported chemical and physical properties of FA.

The database of 76 research papers, project reports and theses was made [5], [9], [21]–[30], [10], [31]–[40],[14], [41]–[50], [15], [51]–[60],[16], [61]–[70], [17], [71]–[80], [18], [81]–[86], [19], [20]. Out of the total number of selected papers, 44 are papers published in journals from the Science Citation Index Thomson Reuters list, 7 are papers published by the American Concrete Institute, one is published by the American Society of Civil Engineers, 7 are master and doctoral thesis and 17 papers are from other sources.

All presented studies were carried out in the period of 31 years, from 1986 to 2018, with the total of 591 different concrete mixtures, 151 CC and 440 HVFAC mixtures, tested for different mechanical properties. In order to carry out the comprehensive analysis of the available results, import parameters which describe the concrete component materials (type of cement, FA, aggregate and water reducing admixtures), concrete mix design and physical and mechanical properties of concrete (slump, compressive strength, splitting tensile strength and modulus of elasticity) at different ages were collected from each study:

1) Cement type;
2) Cement class - 28-day compressive strength;
3) Cement early age strength (Cem. early str.);
4) % of $SiO_2$ in cement (CEM $SiO_2$);
5) % of $Al_2O_3$ in cement (CEM $Al_2O_3$);
6) % of $Fe_2O_3$ in cement (CEM $Fe_2O_3$);
7) % of CaO in cement (CEM CaO);
8) Cement specific surface - Blaine method (CEM Blaine, $cm^2/g$);
9) Cement density ($\gamma_{CEM}$, $kg/m^3$);
10) % of $SiO_2$in FA (FA $SiO_2$);
11) % of $Al_2O_3$in FA (FA $Al_2O_3$);
12) % of $Fe_2O_3$in FA (FA $Fe_2O_3$);
13) % of CaO in FA (FA CaO);
14) LOI in FA (Loss on ignition in FA, %);
15) FA fineness expressed through residue on 45μm sieve (Fine. >45μm, %);
16) FA specific surface - Blaine method (FA Blaine, $cm^2/g$);
17) FA density ($\gamma_{FA}$, $kg/m^3$);
18) Cement mass (CEM , $kg/m^3$);
19) FA mass (FA, $kg/m^3$);
20) Coarse aggregate type (Coars agg. type);
21) Coarse aggregate mass (Coars agg., $kg/m^3$);
22) Fine aggregate type (Fine agg. type);
23) Fine aggregate mass (Fine agg., $kg/m^3$);
24) Maximum aggregate size (Max agg. size, mm);
25) Plasticizer type;
26) Plasticizer amount expressed as a percentage of plasticizer mass to total CM mass ($m_{pl}$/CM, %);
27) FA mass in total CM (FA/CM, %);
28) W/CM ratio;

29) Curing type;
30) Slump (mm);
31) Compressive strength ($f_{cm}$)- Sample type and size;
32)-43) Compressive strength results at 1, 3, 7, 14, 28, 56, 90, 180, 365, 1095, 1825 and 3650 days;
44) Splitting tensile strength ($f_{sp}$) - Sample type and size;
45)-51) Splitting tensile strength at 1, 3, 7, 28, 56, 90, 365 days;
52) Modulus of elasticity (E) - Testing procedure;
53) Modulus of elasticity - Sample type and size;
54)-60) Modulus of elasticity at 3, 7, 14, 28, 90, 180, 365 days.

All collected data were entered into an Excel spreadsheet that is reported in Appendix A (with column numbers as reported above). Although not all selected studies provided all mentioned data, information regarding concrete mix design and results of some mechanical properties were available in all of them.

In a large number of concrete mixtures (306 out of 591), ASTM Type I or CEM I cement was used, in other words cement with minimum 95% of clinker. Other types of cement like ASTM Type II, ASTM Type IP or CEM II were also used in some studies. In some studies, only provided information regarding cement type was that Ordinary Portland cement was used (182 concrete mixtures).

The cement class refers to the standard 28-day compressive strength measured according to the adequate standard for cement classification–EN 197-1 [87] and ASTM C150 and C595 [88], [89]. The early age strength is defined by the strength increase rate in the cement classification. It is usually presented with letters S, N or R referring to slow, normal or rapid strength gain, respectively [87]. In the database this column contains values of early age compressive strength at two or three days or classification S, N, R if this information is available in studies. Figure 1a shows the availability of the cement classification data in the database.

The availability of the chemical and physicals properties of FA in database is presented in Figure 1b. The range of chemical and physical properties of FA and cement used in the selected studies is shown in Table 1. Although only class F FA was used in all studies, the variety of FA chemical and physical properties was still relatively high.

*Table 1. Chemical and physical properties of FA and cement*

| Chemical properties | FA | Cement |
|---|---|---|
| $SiO_2$ (%) | 36.8 - 68.4 | 16.6-39.1 |
| $Al_2O_3$ (%) | 11.1 - 41.0 | 3.1-10.3 |
| $Fe_2O_3$ (%) | 2.7 - 39.7 | 2.0-6.2 |
| CaO (%) | 0.3 - 20.3 | 45.7-70.5 |
| Loss on ignition - LOI (%) | 0.2 - 9.7 | - |
| **Physical properties** | **FA** | **Cement** |
| Fineness (>45 mm, %) | 0.1 - 35.9 | - |
| Specific surface area ($cm^2/g$) | 1874 - 6780 | 2890-5790 |
| Density ($kg/m^3$) | 1900 - 2960 | 2890-3230 |

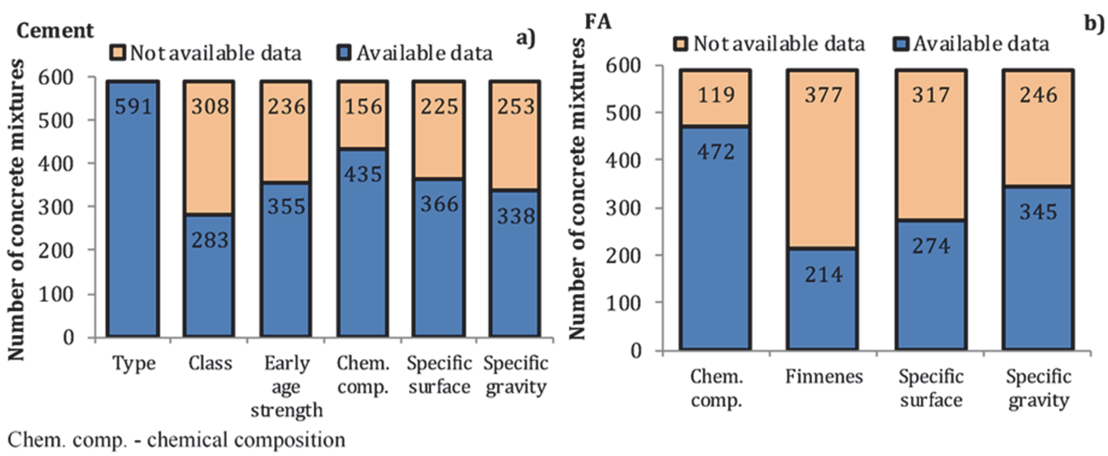



*Figure 1. Number of concrete mixtures with available data regarding a) cement properties and b) FA properties*

The availability of data regarding the aggregate type in database is shown in the following figures: general aggregate type in Figure 2a, maximum aggregate size in Figure 2b and aggregate stone type in Figure 3. The most frequently used aggregate type was crushed coarse (CA) and river sand aggregate (RA) with maximum aggregate size ranging from 10 mm to 32 mm.

Different types of plasticizer were used in most of the studies in different amounts ranging from no plasticizer to 9% (percent of total CM mass) in some studies. The number of studies with different plasticizer amounts is shown in Figure 4a. Plasticizers mostly used were carboxilic, melanine, naphtaline and sulphonated-naphtaleme-formaldehid based.

Figure 4b shows FA content in CM mass in all selected studies and, as it can be seen, in most studies (388 studies) FA makes 40-60% of the total CM. The curing of samples was done in different ways but mostly by standard moist/water curing. Air curing of samples was done in only two studies [29], [53]. The workability of concrete mixtures was available for most of the concrete mixtures – 470 of total 591 mixtures had available information of slump/flow values.

Testing of compressive, splitting tensile strength and modulus of elasticity was done on different samples in different studies. In order to compare these results, all compressive and splitting tensile strength results were recalculated on 150·300 mm cylinders using scaling factors reported in the literature [90], [91]. The scaling factors used for recalculation of compressive strength results were taken as:

- equal to 1 for 152·305 mm cylinder samples,
- equal to 0.975 for 100·200 mm cylinder, 102·204 mm cylinder, 110·220 mm cylinder and 100·100·200 mm prism samples,
- equal to 0.915 for 76·152 mm cylinder sample,
- equal to 0.850 for 150·150·150 mm cube sample,
- equal to 0.750 for 100·100·500 mm prism sample.

The specimen size and shape have a big influence on the splitting tensile strength of concrete [92]–[94]. The scaling factors used for recalculation of splitting tensile strength results were taken as:

- equal to 1.0 for 150·150·150 mm cube samples, 150·150 mm and 150·300 mm cylinder samples,
- equal to 0.9 for 100·100·100 mm cube and 100·200 mm cylinder samples.

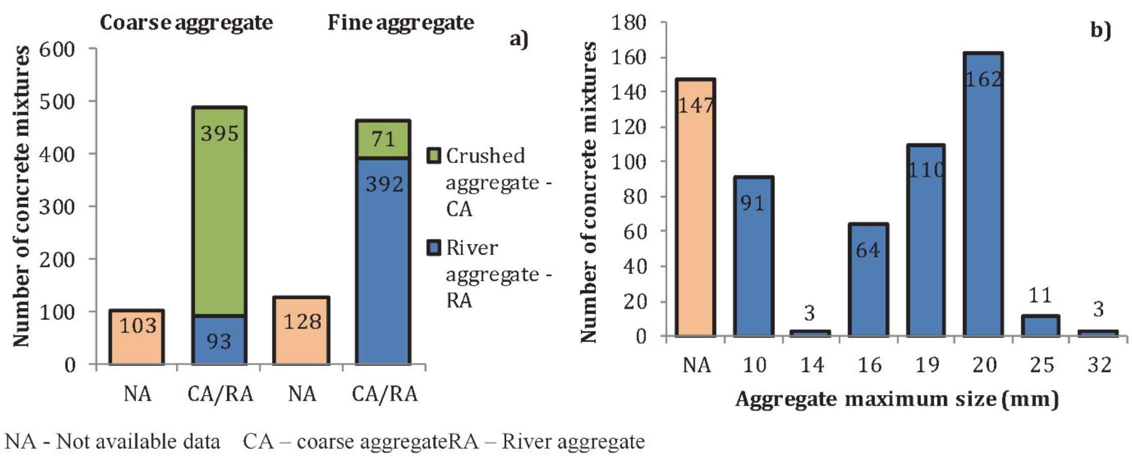



*Figure 2. Number of concrete mixtures regarding a) coarse and fine aggregate type and b) aggregate maximum size*

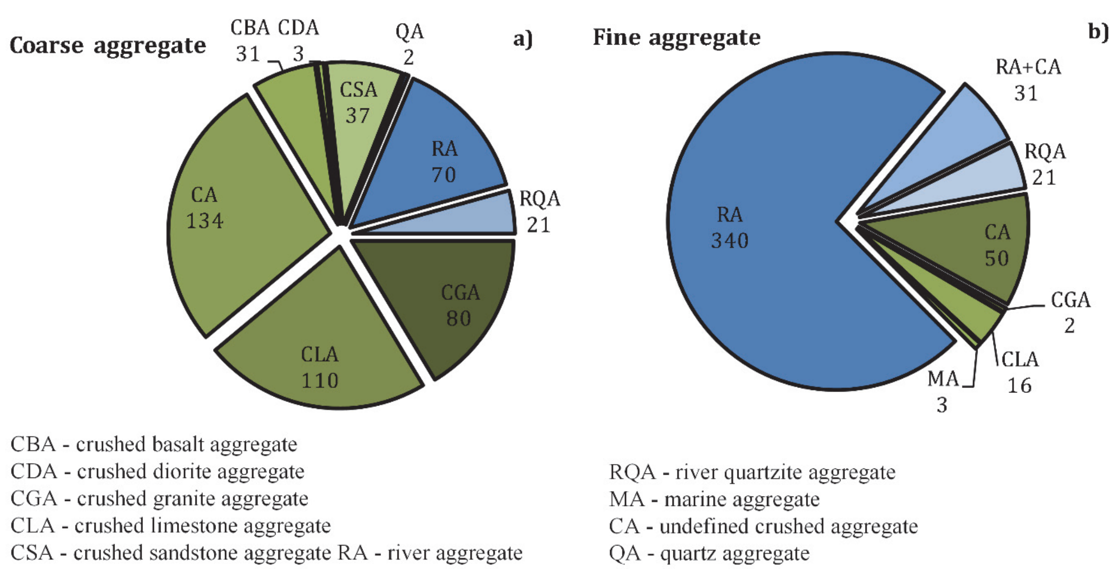



*Figure 3. Number of concrete mixtures regarding a) coarse and b) fine aggregate stone type*

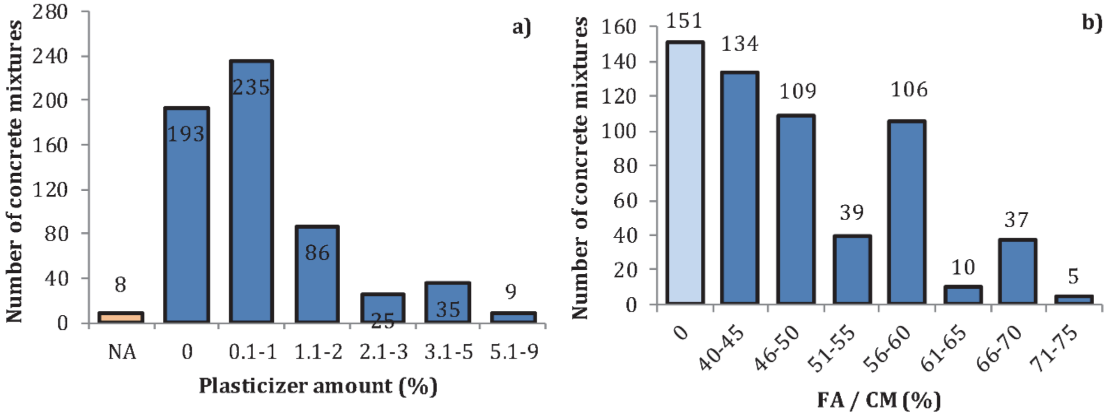



*Figure 4. Number of concrete mixtures regarding a) plasticizer amount and b) FA amount in CM*

As for modulus of elasticity, not only different cylinder sizes were used but also different testing methods. No corresponding factors for modulus of elasticity results recalculation were found in the literature, so this effect was neglected in this research - all modulus of elasticity testing results were used as presented in the selected study.

The compressive, splitting tensile strength and modulus of elasticity were tested at different ages in different studies. The number of concrete samples tested at a certain age regarding compressive and splitting tensile strength and modulus of elasticity are presented in Figures 5 and 6.

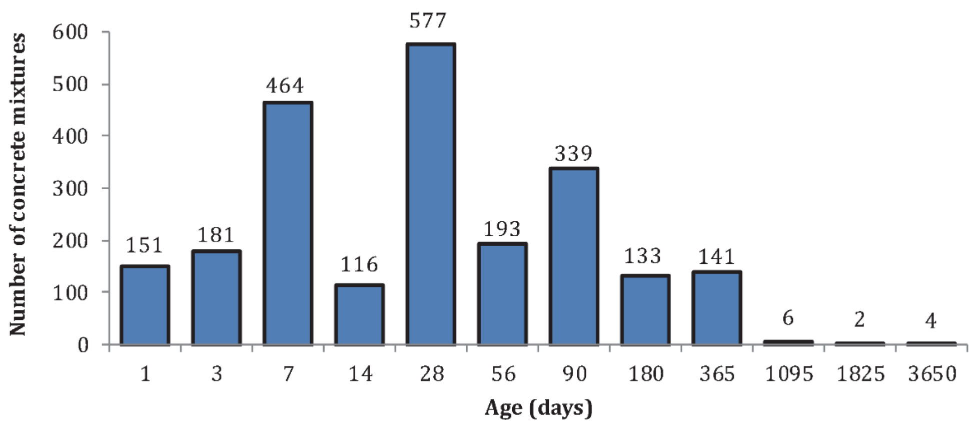



*Figure 5. Number of concrete samples compressive strength tested at different ages*

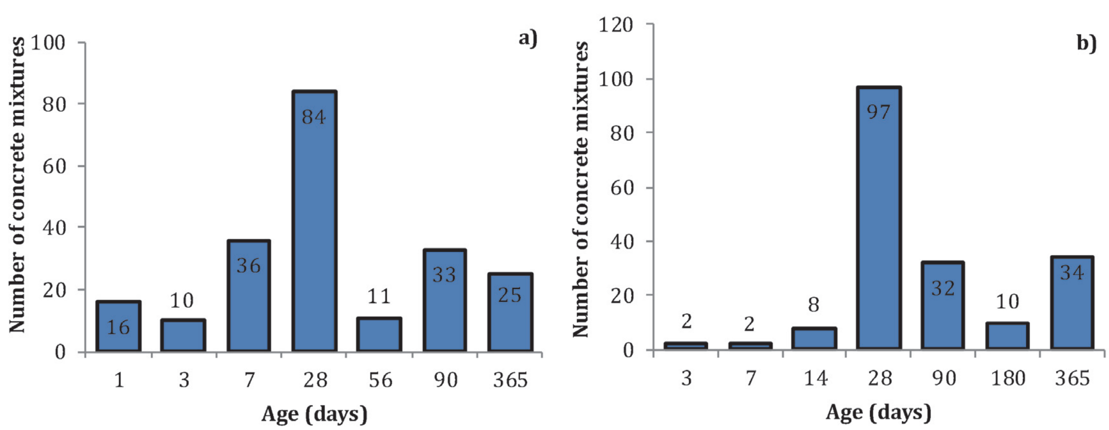



*Figure 6. Number of concrete samples tested at different ages a) splitting tensile strength and b) modulus of elasticity*

In most of the studies, testing was done at the age of 28 days for all mechanical properties. Different target compressive strengths were set in different studies but the largest number of concrete mixtures had 28-day compressive strength between 20 MPa and 50 MPa as shown in Figure 7.

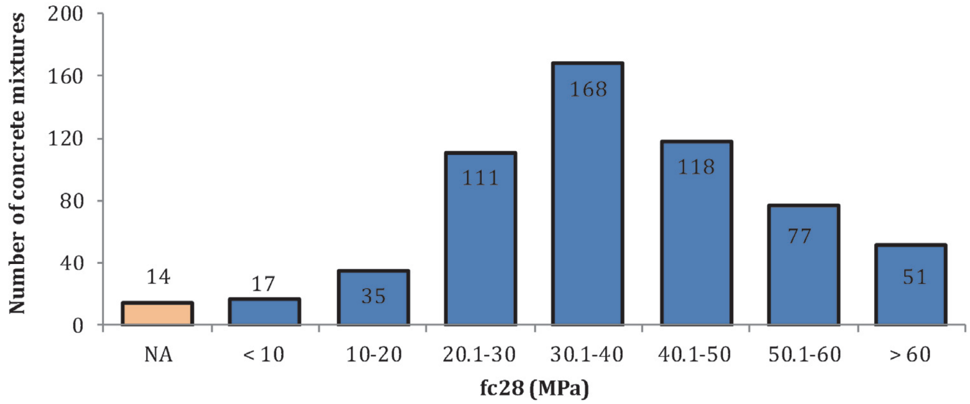



*Figure 7. Number of concrete mixtures regarding 28-day compressive strength test results*

## 3 HVFAC 28-day compressive strength evaluation

For the practical application of HVFAC it is important to establish simple quantitative way to predict the HVFAC compressive strength based on its mix design and using the empirical equations, similar as for CC. So, as a first step, the relationship between the compressive strength and W/CM ratio already established for CC was evaluated for HVFAC.

As the cement type, aggregate type and size as well as the curing conditions strongly affect the concrete strength, only commonly used cement and aggregate types and standard curing conditions were selected for this analysis. High FA content in concrete usually requires plasticizers for achieving adequate workability and it is not surprising that 67% of concrete mixtures from the database contained plasticizers. The influence of the plasticizer on physical and mechanical properties of HVFAC is not fully known. It was considered that the usual amount of plasticizer up to 2-3% of cement mass [90] will not influence the compressive strength in CC and the same assumption was adopted for the HVFAC strength. Having all this in mind, the following HVFAC mixtures were selected from the database:

Concrete mixtures with cement conforming to ASTM type I/II and CEM I/II;

- Mixtures with crushed and river coarse aggregate and maximum size ranging from 10 mm to 25 mm;
- Mixtures made and cured under standard water/moist curing conditions;
- Mixtures with up to 3% of plasticizer.

Figures 8 – 10 show the relation of compressive strength of HVFAC and CC and their W/CM ratio tested at the age of 7 days, 28 days and 90 days, respectively.

The results were plotted in three series regarding the FA/CM ratio (40-50%, 51-60% and 61-75%) and evaluated with the aid of determination coefficient ($R^2$). This coefficient is based on the correlation coefficient (R) which represents the degree of correlation between two variables.

Firstly, it can be seen that the FA amount has a significant influence on the HVFAC compressive strength, separating the series of results with different FA/CM ratio with relatively good correlation. Secondly, the correlation coefficient R was equal or greater than 0.7 for almost all concrete series, indicating that there is a good correlation between the compressive strength and the W/CM ratio [95]. A relatively big scatter of the results was a consequence of different cement and FA types used in different concrete mixtures. The relations in Figures 8 – 10 show that the correlation between HVFAC compressive strength at the age of 7 days, 28 days and 90 days and the W/CM ratio ($R^2$=0.470–0.689) is similar to that of CC ($R^2$=0.448–0.656). The correlation between the HVFAC compressive strength and the W/CM ratio is of the exponential type, as for CC, but it clearly depends on the FA amount – so some modifications are needed to consider the impact of the FA amount and its properties.

In order to establish an adequate relationship between the HVFAC compressive strength and the W/CM ratio, the FA efficiency factor *k* is often used. This concept was first proposed by Smith in 1967 [96]. He defined the FA efficiency factor in such a way that the CC compressive strength to the W/CM ratio relation was also valid for FA concrete introducing the effective W/CM ratio, given as W/(C+*k*·FA).

In a more general way, the FA efficiency factor can be defined as a portion of cement mass that could be replaced by one part of FA without changing the studied property [97]. Class F fly ash can be categorized as a pozzolan, mainly containing silicate, aluminum and iron oxides. In the presence of moisture it reacts with calcium hydroxide – $Ca(OH)_2$ formed by the cement hydration. First, the dissolution of FA's amorphous $SiO_2$ and $Al_2O_3$ framework by hydroxide ions and generated heat during the early hydration of cement initiates the pozzolanic reaction. Afterwards, free silicate and aluminate anions react with $Ca(OH)_2$ to form an amorphous calcium silicate aluminate phase. This reaction continues until $Ca(OH)_2$ is present in the concrete pore solution and until the hydrated gel fills in the capillary pores in concrete. The dissolution of FA is strongly influenced by the FA fineness, and can be initiated faster if FA particles are smaller in size - the pozzolanic reaction develops at higher extent if finer FA is used.

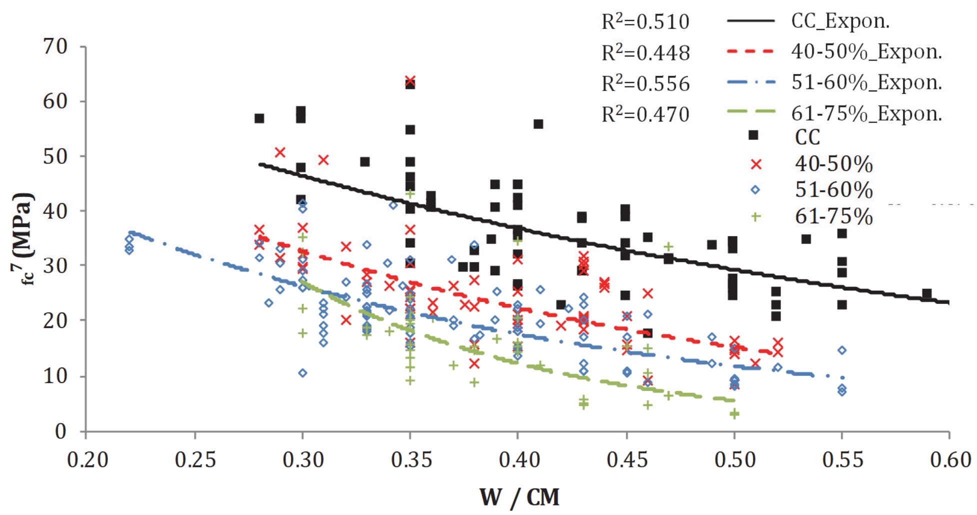



*Figure 8. 7-day compressive strength of the HVFAC and CC versus the W/CM ratio*

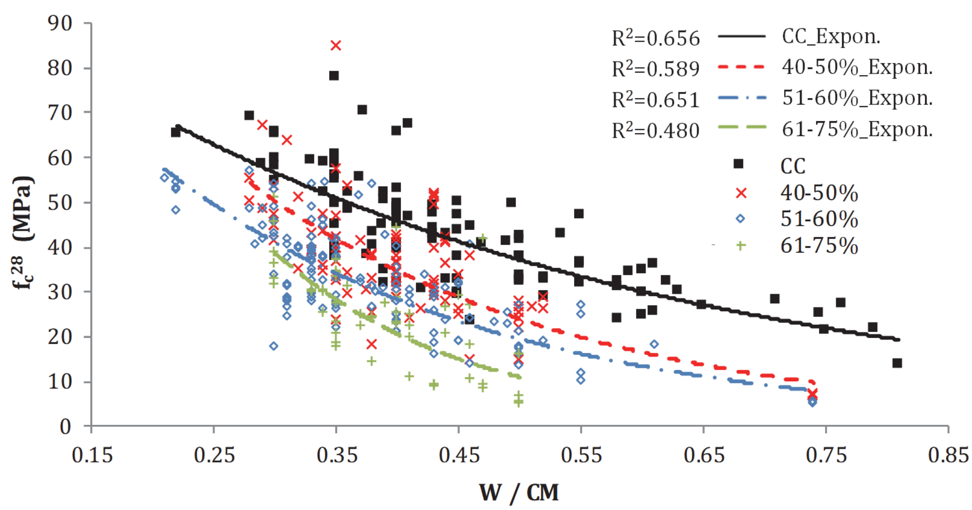



*Figure 9. 28-day compressive strength of the HVFAC and CC versus the W/CM ratio*

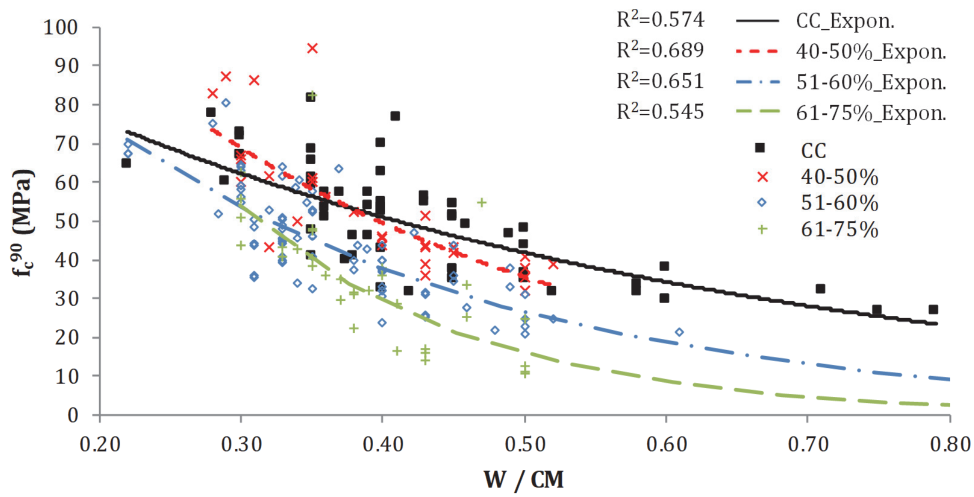



*Figure 10. 90-day compressive strength of the HVFAC and CC versus the W/CM ratio*

So, the capacity of FA to act as a binder equivalent to cement is influenced by many factors, but mostly by the amount, the physical and mechanical properties of FA and cement, the age of concrete and curing conditions [97]–[101]. The list of relevant research papers regarding the FA efficiency is shown in Table 2 along with all parameters analyzed in these studies. Proposed predictions for *k* factor given in Table 2 were re-evaluated using HVFAC results from the database.

*Table 2. Relevant research proposals regarding efficiency factor k [102]*

| Study | FA class | FA/CM (%) | Parameters | Efficiency factor k |
|---|---|---|---|---|
| [97] | F / C | 15-75 | FA/CM ratio (p), concrete age. | $k_7 = 2.67 \cdot p^2 - 3.75 \cdot p + 1.45$<br>$k_{28} = 2.78 \cdot p^2 - 3.80 \cdot p + 1.64$<br>$k_{90} = 2.50 \cdot p^2 - 3.59 \cdot p + 1.73$ |
| [101] | F / C | 10-20 | Activity index (AI), active silica content in FA ($\gamma_S$), silica content in C and FA, concrete age, W/C ratio. | $k = 1 + 4 \cdot (AI - 1)/(1 - 0.5a)$<br>$a$ - parameter depending on time and curing;<br>$k = \gamma_S \cdot \frac{f_{S,P}}{f_{S,C}} \cdot \left(1 - a\frac{W}{C}\right)$<br>$f_{S,P}$ - weight fraction of $SiO_2$ in FA;<br>$f_{S,C}$ - weight fraction of $SiO_2$ in C. |
| [99] | - | 10-49 | FA fineness (Blaine method), FA/C ratio, concrete age. | $k_7 = 0.21 \cdot \exp\left(-0.43 \times \frac{FA}{C}\right) \cdot \alpha_2$<br>$k_{28} = 0.42 \cdot \exp\left(-0.72 \times \frac{FA}{C}\right) \cdot \alpha_2$<br>$k_{90} = 0.85 \cdot \exp\left(-1.36 \times \frac{FA}{C}\right) \cdot \alpha_2$<br>$\alpha_2 = 1.14 \cdot 10^{-4}(\text{Blaine} - 2500) + 1$ |
| [103] | F | 10-80 | FA/CM percentage (P), concrete age. | $k_7 = 0.9 - 0.1 \cdot \log_e P$<br>$k_{28} = 1.2 - 0.14 \cdot \log_e P$ |
| [104] | C | 60-90 | CaO, $SiO_2$, $Al_2O_3$ content in FA and cement (C, S, A), concrete age. | $k(t) = H(t) \cdot \frac{C}{S+A}$ *<br>$H(t)$ - 0.4; 0.5; 0.6; 0.7; 0.8; 0.8; 0.8 for 7, 14, 28, 56, 84, 112 and 168 days respectively. |
| [105] | - | 10-70 | FA /CM ratio (p), concrete age (t). | $k_t = 1.25 + 0.14 \cdot \log_e t - 3.90 \cdot p + 2.75 \cdot p^2$ |

*C/(S+A) = $CaO/(SiO_2+Al_2O_3)$

One of the first research regarding the efficiency of CM (FA, silica fume and ground granulated blast-furnace slag) defined by *k* factor was performed by Babu [97], [98], [106]–[108]. Researchers assumed that the FA efficiency is mostly influenced by the W/CM ratio, FA/CM ratio and age. They re-evaluated the results from previous studies and defined the FA efficiency at different ages - 7 days, 28 days and 90 days for FA replacement levels from 15% to 75% (Table 2). The selection of the results was done in the way that only mixtures with maximum aggregate size of 20 mm, plasticizer amount less than 2%, cured under normal conditions were used for the evaluation.

The evaluation of the efficiency factor proposed by Babu and Rao [97] was done on the previously selected results from the database. Figure 11 shows the relationship between the 28-day compressive strength of CC and HVFAC experimental values and the W/(C+*k*·FA) ratio with *k* values proposed by Babu and Rao [97]. It can be seen that similar correlation between CC and HVFAC results can be obtained by applying the FA efficiency factor proposed by Babu and Rao [98] with slightly stronger correlation for HVFAC ($R^2$=0.656 for CC and $R^2$=0.704 for HVFAC).

Predictions for *k* factor given by Rajamane et al. [103] and Yeh [105] depend on the same two variables as in Babu's prediction – the FA/CM ratio and concrete age. Evaluation of their *k* factor predictions on the results from own database is shown in Figures 12 and 13. Similar correlation for HVFAC and CC compressive strength results can be seen with better correlation obtained by using Yeh [105] prediction.

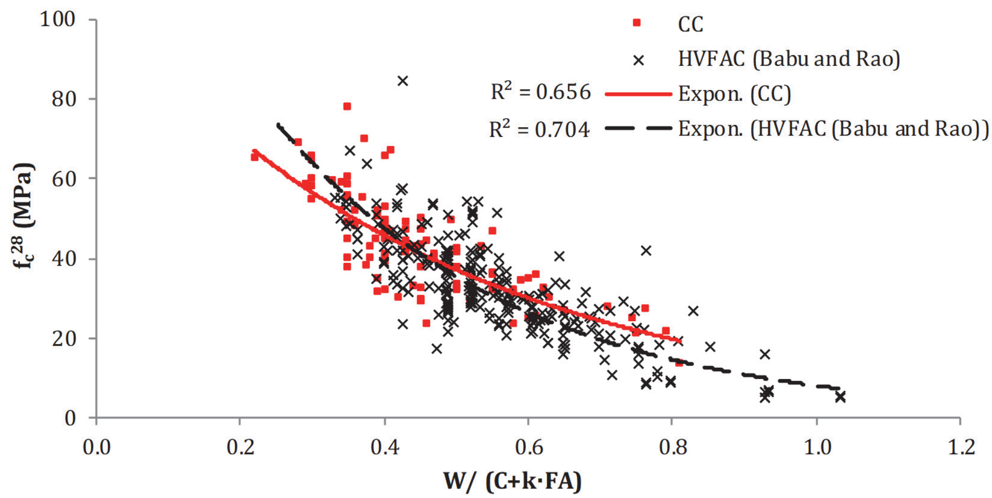



*Figure 11. Relationship between 28-day compressive strength and W/(C+k·FA) [98]*

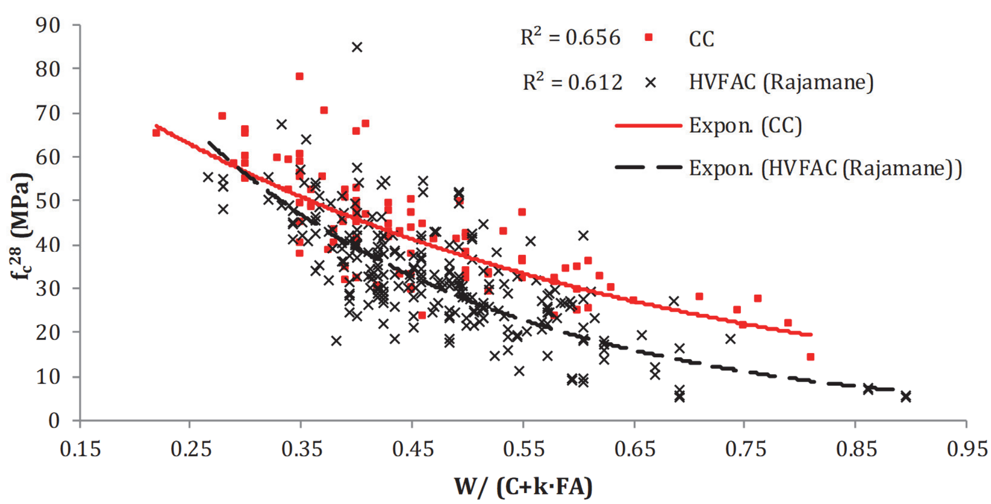



*Figure 12. 28-day compressive strength versus W/(C+k·FA) [103]*

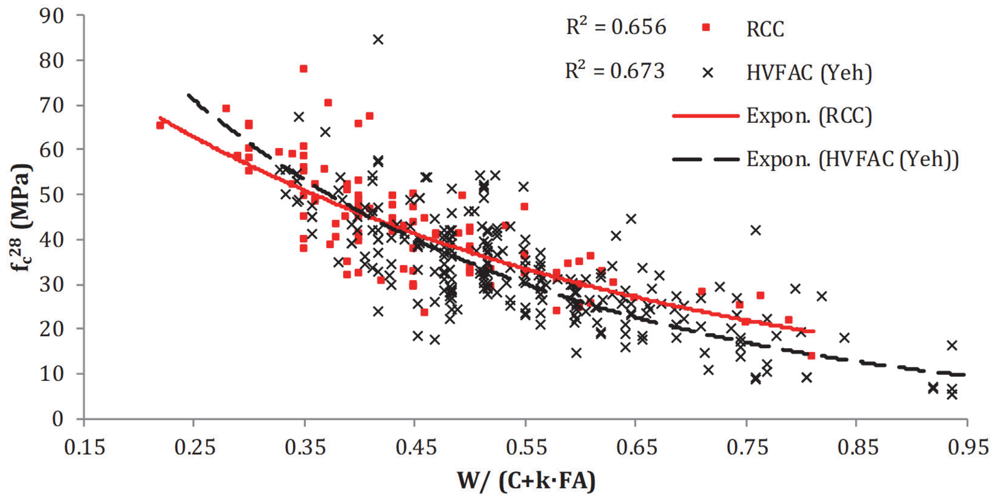



*Figure 13. 28-day compressive strength versus W/(C+k·FA) [105]*

To improve the correlation between the HVFAC compressive strength and W/(C+*k*·FA) factor parameters defining FA and cement properties should be included. For instance, Papadakis investigated the influence of active silica (active $SiO_2$) content in FA on the efficiency of FA in concrete [101], [109]–[111]. According to Papadakis et al. (2002) the activity of CM was greatly influenced by the amount of active $SiO_2$ in FA and cement and the FA activity index. According to the defined procedure, given in EN 450-1 [112], the FA activity index is being tested on mortars made with 25% of FA in CM mass. Papadakis et al. [101] analyzed the influence of these two parameters on the efficiency of FA in concrete mixtures made with 10% to 20% of FA in CM. Two different predictions for k factor were proposed by the authors, as shown in Table 2. The predictions proposed by Papadakis et al. [101] were not re-evaluated in this study due to the lack of available results regarding FA and cement active silica content and the FA activity index for HVFAC mixtures in the database.

Another important parameter influencing the FA efficiency is its fineness [97], [101]. A study conducted by Hwang et al. [99] evaluated the efficiency of FA as the function of the FA content, Blaine specific surface area and concrete age. The authors highlighted that the FA efficiency is strongly influenced by the FA and cement amount ratio, but suggested that the effect of the FA fineness should also be included (Table 2). In order to re-evaluate the *k* factor proposed by Hwang et al. [99] selected CC and HVFAC mixtures from the database were analyzed. Only studies with available results of FA Blaine specific surface area were chosen from the database (211 HVFAC mixtures). The relationships between the CC and HVFAC 28-day compressive strength results and the W/(C+k·FA) ratio proposed by Hwang et al. [99] are shown in Figure 14. The

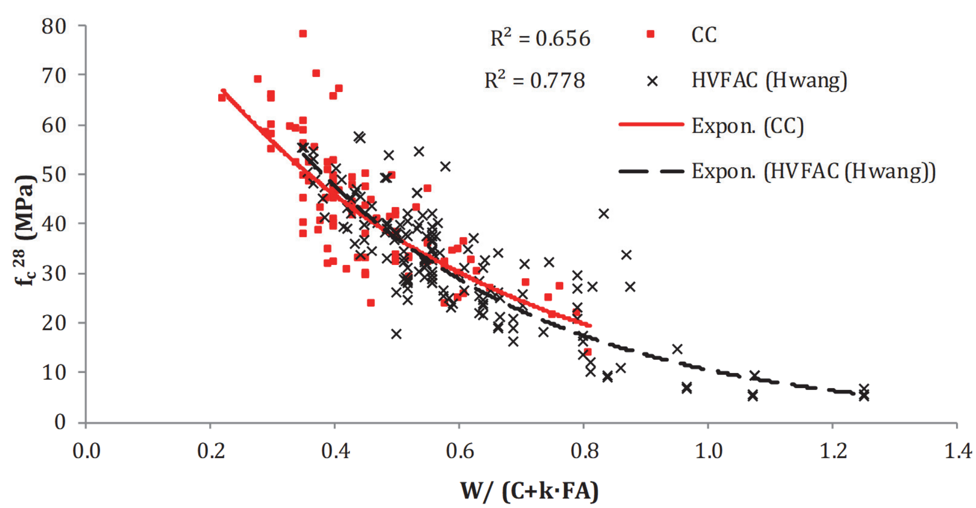



*Figure 14. 28-day compressive strength versus W/(C+k·FA) [99]*

strong correlation shown in Figure 14 ($R^2$=0.778 for HVFAC) indicates that the fineness is an important factor influencing FA efficiency.

The Blaine method is widely used for the characterization of the cement fineness and it is defined in the EN 196-6 [113]. However, this method is not included in the EN 450-1 for the use of FA in concrete [112]. One of the basic assumptions regarding the Blaine method testing is that the material particles are mostly spherical with no particles that are highly irregular in shape [114]. However, FA particles can be irregular in shape with a certain number of unburned coal residues and inter-particle heterogeneity [115]. Hence, a special attention is needed when selecting measuring techniques (which were developed for cement) in the characterization of FA [114], [116]. This can be a disadvantage of the FA efficiency method proposed by Hwang et al. [99]. Nevertheless, fineness, particularly that of its glassy phase, is considered to be an important factor influencing the FA efficiency [117].

The amount of reacted FA greatly depends on its glassy phase - reactive $SiO_2$ and $Al_2O_3$ content and on the amount of available $Ca(OH)_2$ present in the concrete matrix. Hannesson [52] conducted research in order to determine the FA efficiency as a function of FA and cement chemical composition. He concluded that the amount of CaO, $SiO_2$ and $Al_2O_3$ in the cement and FA was an important factor influencing the FA concrete compressive strength. Since these three chemical compounds are important for both early and long-term strength, the FA efficiency was presented as the function of the CaO mass to the sum of $SiO_2$ and $Al_2O_3$ mass ratio in total CM for different concrete age.

In a paper published by Kuder et al. (2012), the summary of the research done by Hannesson [52] was presented. The evaluation of the FA and granulated blast furnace slag efficiency in different concrete mixtures was done. The proposed efficiency factor (Table 2) was re-evaluated in this study on the selected results from the database. Out of all results in the database, only the ones with available data on CaO, $SiO_2$ and $Al_2O_3$ content in cement and FA were used for the analysis (334 HVFAC mixtures). The relationships between the 28-day compressive strength and the W/(C+*k*·FA) ratio are shown in Figure 15 for Kuder et al. [104] *k* factor predictions. Similar correlation was obtained for the CC and HVFAC results ($R^2$=0.656 for CC and $R^2$=0.546 for HVFAC).

The previous analysis showed that HVFAC can be defined with the same exponential type of compressive strength and W/CM ratio relationship if the FA efficiency factor was introduced. Looking at Figures 11-15, it can be concluded that Hwang et al. [99] prediction proposal provided the strongest correlation between the HVFAC compressive strength and W/(C+*k*·FA) ratio. This is understandable since this is the most complex prediction model reflecting the influence of FA/CM ratio, FA fineness and concrete age on the FA reactivity. On the other hand, the factor proposed by Kuder et al. (2012) introducing the CaO, $SiO_2$ and $Al_2O_3$ content in FA and cement is considered to reflect FA reactivity better than the FA/CM mass ratio. With a factor of that type, the mass ratio of the most important oxides influencing pozzolanic activity of FA is considered. Since the FA reactivity is also influenced by its fineness, the attempt was made to modify Kuder et al. [104] proposal by introducing FA fineness into the prediction model. For that purpose, the FA density was chosen because it can be determined more reliably than the Blaine specific surface area; besides, it is commonly used in the FA characterization as the fineness indicator.

To propose the modification of the C/(S+A) factor type by incorporating the FA density, the following procedure was applied:

- Evaluation of the selected empirical equations defining the relationship between the compressive strength and W/CM ratio of CC;
- Calculation of necessary coefficients for the use of these equations;
- Calculation of the experimental *k* factor values for the HVFAC from the database;
- Proposing the equation for *k* factor calculation.

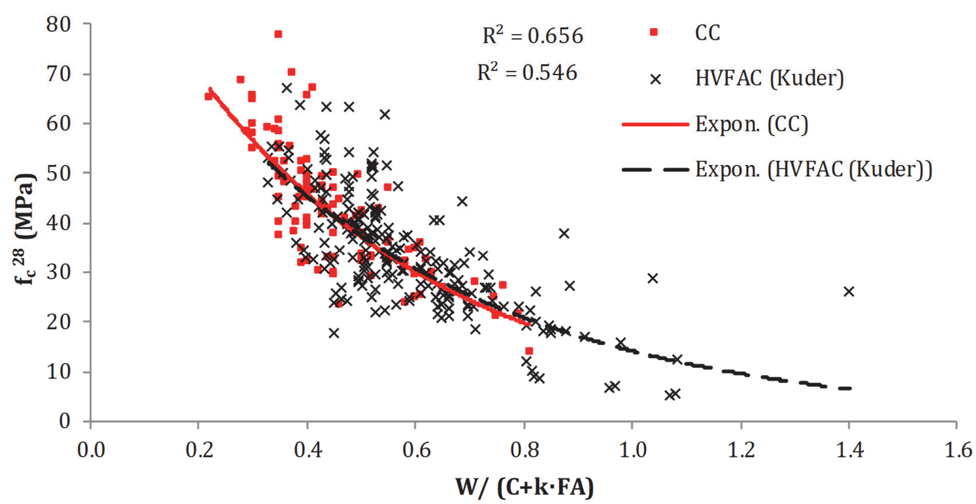



*Figure 15. 28-day compressive strength versus W/(C+k·FA) [104]*

One of the main reasons for analyzing the FA efficiency is the need to use the empirical equations for compressive strength predictions in order to determine the concrete mix design and component material proportion. There are few empirical equations used for the compressive strength prediction of CC and they are all the function of the W/C ratio accounting for different parameters of influence. The most commonly used empirical equations are Abrams, Bolomey, Feret and Baljejev [118]–[125]. In this study Bolomey, Baljejev and Feret equations were selected for evaluation in the following forms:

Bolomey equation:

$$f_c = A \cdot \left( \frac{1}{\frac{W}{(C + k \cdot FA)}} - 0.5 \right) \tag{1}$$

where:
W water amount (kg/m$^3$);
C cement amount (kg/m$^3$);
FA FA amount (kg/m$^3$);
k FA efficiency factor;
A coefficient defining cement strength and aggregate type.

Baljejev equation:

$$f_c = \frac{B}{\left(\frac{W}{C + k \cdot FA}\right)^{1.5}} \tag{2}$$

where:
B coefficient defining cement strength and aggregate type.

Feret equation:

$$f_c = \frac{K}{\left(1 + \frac{W}{C + k \cdot FA} \cdot \frac{\gamma_{sc}}{\gamma_w}\right)^2} \tag{3}$$

where:
K parameter depending on the cement class;
$\gamma_{sc}$ density of cement;
$\gamma_w$ density of water.

The empirical coefficients A, B and K in Bolomey, Baljejev and Feret equations were calculated based on the experimental results of the CC made with the same cement, aggregate and plasticizer type and cured under the same conditions as the HVFAC. In this way, it was further possible to apply calculated empirical coefficients when predicting the HVFAC compressive strength. Out of all studies in the database, only the ones with available data regarding concrete mix design, chemical composition of FA and cement, CC concrete mixture and 28-day compressive strength were selected. After applying these filters to the database, 41 studies with concrete mixtures remained for further analysis. The selected concrete mixtures were divided into two groups, 285 HVFAC mixtures and 88 CC mixtures. The coefficients A, B and K in Bolomey, Baljejev and Feret equations were calculated for each referent CC in each study using the following equations:

$$A_i = \frac{f_c^{RCC}}{C/W - 0.5} \tag{4}$$

$$B_i = f_c^{RCC} \cdot \left(\frac{W}{C}\right)^{1.5} \tag{5}$$

$$K_i = f_c^{RCC} \cdot \left(1 + \frac{W}{C} \cdot \frac{\gamma_{sc}}{\gamma_w}\right)^2 \tag{6}$$

where:
i number of different studies;
$f_c^{RCC}$ experimental 28-day compressive strength of CC (MPa);
C, W cement and water mass in CC;
$\gamma_{sc}$ density of cement, if not available taken as 3150 kg/m$^3$;
$\gamma_w$ = 1000 kg/m$^3$.

In some studies, more than one CC mixture was used and in that case $A_i$, $B_i$ and $K_i$ coefficients were taken as the mean values of all CC mixtures in that study. This procedure was justified given that all CC in one study were made with the same cement and aggregate type.

In order to choose one of these three empirical equations for further analysis the FA efficiency factor ($k^{EXP}$) was calculated from the experimental HVFAC compressive strength results using each of them with $k=k^{EXP}$.

The results of the calculated $k^{EXP}$ for all 285 HVFAC mixtures (sample number ranging from 1 to 285) are shown in Figure 16. It can be seen that the Bolomey and Baljejev equations gave similar $k^{EXP}$ values while the Feret equation yielded slightly higher $k^{EXP}$ values. Bolomey equation was selected for further FA efficiency evaluation.

The next step was to propose the FA efficiency factor as a function of C/S+A ratio and FA fineness expressed with FA density. The evaluation was done on selected studies from the database that had available both chemical composition and density of FA. These criteria yielded 180 HVFAC mixtures for further evaluation. The aim was to obtain the best fit with the experimentally obtained values for *k* ($k^{EXP}$). The general form for the efficiency coefficient is proposed as:

$$k = a \cdot \gamma_{FA} \cdot \frac{C}{S + A} \tag{7}$$

where:
$\gamma_{FA}$ FA density (kg/m$^3$).

The coefficient *a* was fitted in order to match as closely as possible the values of $k^{EXP}$ and after few iterations the following equation was adopted as the best fit:

$$k = \frac{\gamma_{FA}}{3150} \cdot \frac{C}{S + A} \tag{8}$$

The compressive strength of the selected HVFAC mixtures was calculated using the Bolomey equation and the proposed *k* factor defined by Kuder et al. [104] and own modification given in the equation (8). The results are shown in Table 3 and plotted versus the experimental strength in Figure 17. Both equality and mean lines are shown in all figures of the same type as Figure 17 for visual clarity.

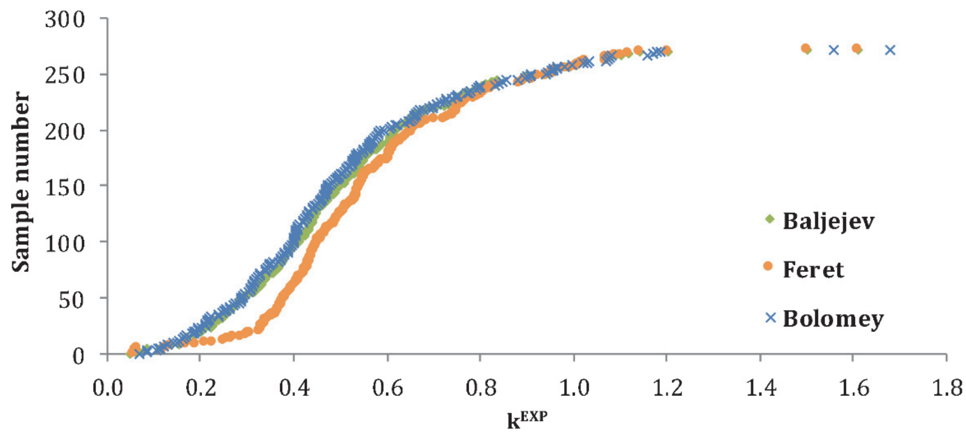



*Figure 16. Experimental values of k factor for all 285 HVFAC mixtures*

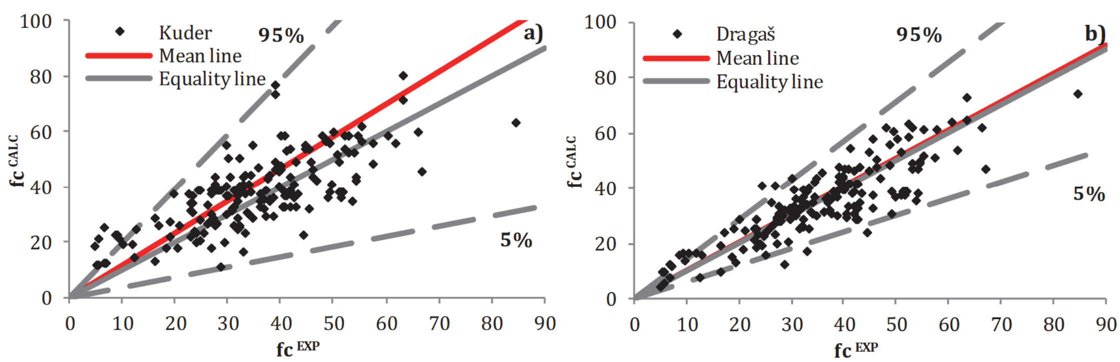



*Figure 17. HVFAC compressive strength calculated using different k factor values a) Kuder et al. [104] proposal and b) own proposal*

Significantly lower CoV was calculated for the application of own proposal for *k* factor compared with the k factor proposed by Kuder et al. [104] as can be seen in Table 3. So the incorporation of the FA density as a measure of FA fineness in the k factor proposed by Kuder et al. [104] led to the improvement of the compressive strength prediction, and more importantly, to the decrease of the results scattering. Equation (8) can be used to predict the 28-day compressive strength of HVFAC made with 40%-75% of class F FA and normal weight aggregate.

*Table 3. Calculated-to-experimental HVFAC compressive strength predictions*

| | Sample No. | Mean Values | St. Deviation | CoV (%) | $LCL_{5\%}$* | $UCL_{95\%}$# |
|---|---|---|---|---|---|---|
| Kuder | 180 | **1.17** | 0.48 | 41.57 | 0.37 | 1.96 |
| Dragaš | 180 | **1.02** | 0.25 | 24.54 | 0.61 | 1.42 |

*Lover confidence limit $LCL_{5\%}$ = Mean – 1.645 St.Dev.
#Upper confidence limit $UCL_{95\%}$ = Mean + 1.645 St.Dev.

## 4 Compressive strength development over time

European Standard EN 1992-1-1 [12] defines the following equation for the compressive strength development of cement concrete:

$$f_{cm}(t) = f_{cm}(28) \cdot \beta_{cc}(t) = f_{cm}(28) \cdot EXP\left\{s \cdot \left(1 - \sqrt{\frac{28}{t}}\right)\right\} \quad (9)$$

where:
$f_{cm}(28)$ mean 28-day compressive strength;
t days;
s coefficient depending on the cement type and class.

The coefficient *s* is defined for three groups of cement as (32.5, 42.5 and 52.5 refer to 28-day compressive strength in MPa):

- 0.20 - cement strength classes CEM 42.5 R, CEM 52.5 N and CEM 52.5 R;
- 0.25 - cement strength classes CEM 32.5 R, CEM 42.5 N;
- 0.38 - cement strength classes CEM 32.5 N.

Application of this equation was tested on CC and HVFAC mixtures from the database with available information regarding cement strength class and early age cement strength. The compressive strengths at different ages for the selected CC and HVFAC mixtures were calculated using equation (9) and experimental value of 28-day compressive strength. The experimental versus calculated CC and HVFAC compressive strengths for 1-14 days and 56-365 days are shown in Table 4 and in Figure 18 (for HVFAC).

Looking at the statistical descriptors in Table 4 and Figure 18 it can be seen that the early age HVFAC compressive strength is overestimated and later age HVFAC compressive strength is underestimated when equation (9) is applied. This trend was expected having in mind that FA pozzolanic reaction takes place if there is available $Ca(OH)_2$ in concrete matrix – it starts after the beginning of hydration, approximately at the age of 7–14 days or later [8], [117]. So, the equation (9) defined in EN 1992-1-1 [12] should be modified for the HVFAC compressive strength development over time. The easiest way to do it is by modifying the *s* coefficient.

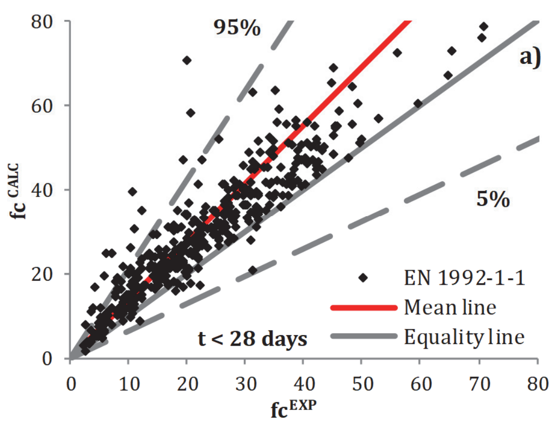
There are several proposals for the *s* coefficient modification in literature. The evaluation of the HVFAC compressive strength development over time was done by Yoon et al. [42] by analysing the HVFAC made with 50% and 60% of class F FA and different W/CM ratios. The researchers concluded that the W/CM ratio is also an important factor influencing the strength gain, especially in high FA content concrete made with low water amount. They proposed the modified *s* coefficients for different FA amount and W/CM ratios regardless of the cement type as follows:

- s = 0.57 ± 0.08 for FA/CM=0.5 for all W/CM;
- s = 0.56 ± 0.02 for FA/CM=0.6 for and W/CM = 0.3;
- s = 0.89 ± 0.05 for FA/CM=0.6 for all other W/CM.

*Table 4. Calculated-to-experimental compressive strength ratio at different ages*

| | Sample No. | Mean Values | St. Deviation | CoV (%) | $LCL_{5\%}$* | $UCL_{95\%}$# |
|---|---|---|---|---|---|---|
| CC_EN 1992-1-1, t <28 days | 185 | **1.00** | 0.21 | 21.16 | 0.65 | 1.34 |
| HVFAC_EN 1992-1-1, t <28 days | 434 | **1.39** | 0.45 | 32.24 | 0.65 | 2.12 |
| CC_EN 1992-1-1, t > 28 days | 162 | **0.99** | 0.07 | 6.89 | 0.88 | 1.11 |
| HVFAC_EN 1992-1-1, t >28 days | 450 | **0.81** | 0.13 | 16.49 | 0.59 | 1.03 |

*Lover confidence limit $LCL_{5\%}$ = Mean – 1.645 St.Dev.
#Upper confidence limit $UCL_{95\%}$ = Mean + 1.645 St.Dev.



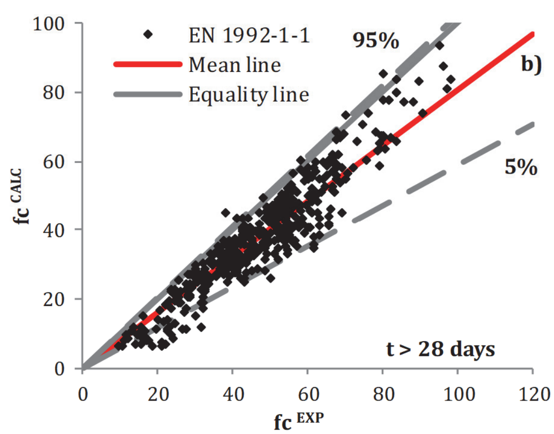




*Figure 18. Relationship between the calculated (EN 1992-1-1) and experimental HVFAC compressive strength for ages a) 1-14 days and b) 56-365 days*

Due to relatively wide range proposed for *s* coefficient and the fact that cement type was not included in the proposed modifications, these proposals were not tested against the test results.

Chen et al. [126] proposed the modification of the EN 1992-1-1 equation (10) by using new *s* coefficient defined as a function of the C/(S+A) ratio, mentioned before, as follows:

$$\beta_{cc}(t)=\begin{cases} EXP\left\{s\cdot\left(-0.38\cdot\frac{C}{S+A}+2.12\right)\cdot\left(1-\sqrt{\frac{28}{t}}\right), \quad t<28\,days\right\} \\ EXP\left\{s\cdot\left(-1.15\cdot\frac{C}{S+A}+3.70\right)\cdot\left(1-\sqrt{\frac{28}{t}}\right), \quad t>28\,days\right\} \end{cases} \tag{10}$$

where:

s coefficient defined in EN 1992-1-1 [12] in equation (10) depending on the cement type.

They concluded that the C/(S+A) ratio influenced the compressive strength development in different ways for the ages before and after 28 days. According to the authors, the increase of C/(S+A) ratio causes increase of the compressive strength before 28 days, and the decrease of strength after 28 days [126]. This can be explained by the fact that the cement hydration is dominant at early ages when more CaO is favourable. At later ages, the pozzolanic reaction takes place and more $SiO_2$ and $Al_2O_3$ is needed.

The development of FA concrete compressive strength was also studied by Bhaskara et al. [82] in their research regarding concretes containing up to 75% of FA in total mass of CM. Based on the results from literature and own experimental results they proposed the modification of coefficient *s* defined in EN 1992-1-1 (equation 10) as a function of FA amount in total CM mass as:

$$s_{mean}=0.298e^{0.0134p} \tag{11}$$

where: $p=\frac{FA}{C+FA}\times 100$

Bhaskara et al. [82] also proposed the equations for predicting the 95% confidence limit (i.e. the lower 5% significance level of s) for obtaining a conservative estimation of mean compressive strength:

t < 28 days: $s_{mean}=0.268e^{0.0132p}$ (12)

t > 28 days: $s_{mean}=0.315e^{0.0135p}$ (13)

The evaluation of Chen et al. (2017) and Bhaskara et al. [82] proposal for *s* coefficient was done by comparing the calculated and experimental values of the compressive strength for the ages before and after 28 days as shown in Table 5 and in Figures 19 and 20. Chen et al. [126] proposal was evaluated on the selected results from the database that had available information regarding cement and FA chemical composition by applying the equation (10) in equation (9). Evaluation of the Bhaskara et al. proposal for *s* coefficient was done by applying equations (12) and (13) in equation (9). The HVFAC compressive strength was also calculated using s=0.38 (as for cement class S) as proposed by Bamforth et al. [127] for concretes with more than 35% of FA in total CM (Table 5 and Figure 21).

*Table 5. Calculated-to-experimental HVFAC compressive strength ratio at different ages*

| | Sample No. | Mean Values | St. Deviation | CoV (%) | $LCL_{5\%}$* | $UCL_{95\%}$# |
|---|---|---|---|---|---|---|
| Chen et al., t < 28 days | 330 | **0.96** | 0.24 | 25.35 | 0.56 | 1.35 |
| Bhaskara et al., HVFAC, t < 28 days | 674 | **0.85** | 0.24 | 28.72 | 0.45 | 1.25 |
| s=0.38, t < 28 days | 674 | **1.08** | 0.27 | 24.78 | 0.64 | 1.53 |
| Chen et al. t > 28 days | 302 | **1.06** | 0.16 | 14.89 | 0.80 | 1.31 |
| Bhaskara et al., HVFAC, t > 28 days | 583 | **0.99** | 0.15 | 14.84 | 0.75 | 1.24 |
| s=0.38, t > 28 days | 583 | **0.87** | 0.13 | 15.24 | 0.65 | 1.09 |

*Lover confidence limit $LCL_{5\%}$ = Mean – 1.645 St.Dev.

#Upper confidence limit $UCL_{95\%}$ = Mean + 1.645 St.Dev.

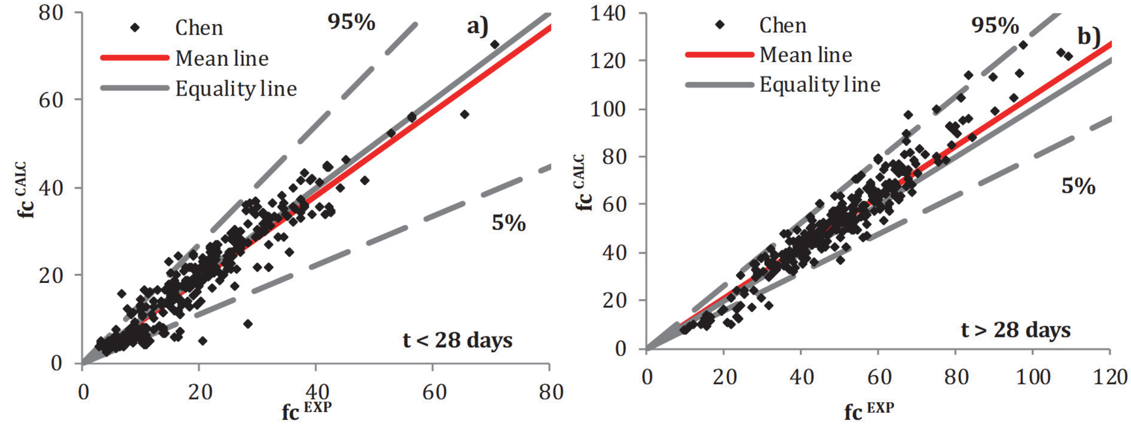



*Figure 19. Relationship between the calculated [126] and experimental HVFAC compressive strength for ages a) 1-14 days and b) 56-365 days*

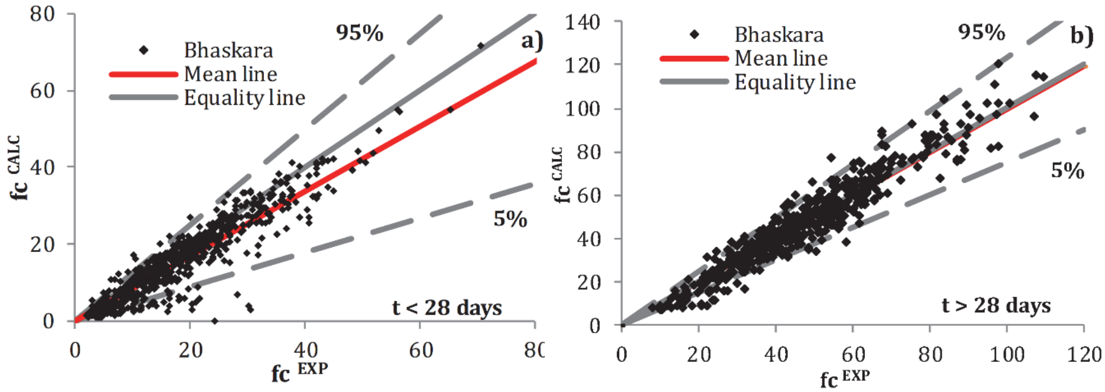



*Figure 20. Relationship between the calculated (Bhaskara et al. 2018) and experimental HVFAC compressive strength for ages a) 1-14 days and b) 56-365 days*

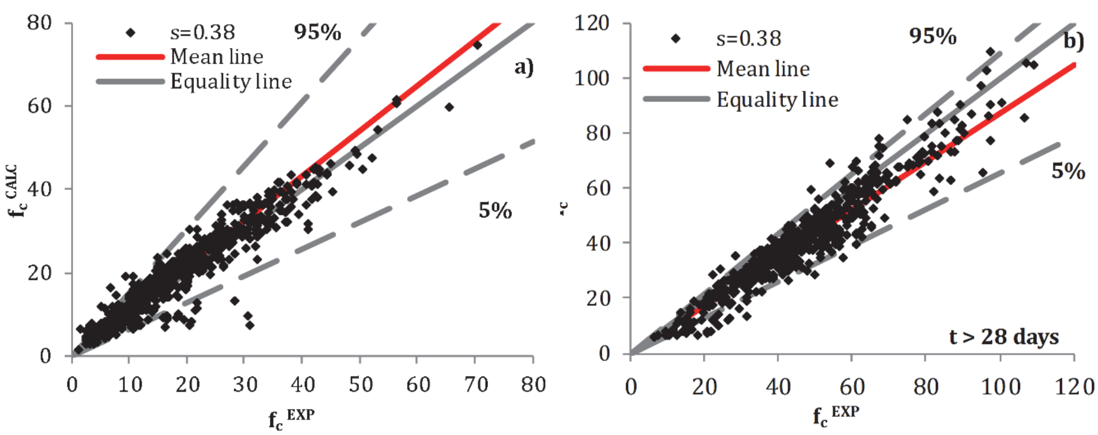



*Figure 21. Relationship between the calculated (s=0.38) and experimental HVFAC compressive strength for ages a) 1-14 days and b) 56-365 days*

Considering means and CoVs, the most accurate prediction of compressive strengths at ages before 28 days was obtained with Chen et al. (2017) proposal. Compressive strengths at ages after 28 days were most accurately predicted with Bhaskara et al. proposal. Looking integrally, Chen et al. prediction model (equation 10) in combination with EN 1992-1-1 equation (9) can be recommended - it provided similar accuracy and variation as for CC (Table 4 and 5) so no further modifications were needed.

## 5 Modulus of elasticity

Modulus of elasticity is mostly influenced by the concrete age, cement (binder) paste, aggregate type, interfacial transition zone and the porosity of concrete [90]. As already mentioned, available results regarding modulus of elasticity from different studies were obtained on cylindrical samples 100·200 mm or 150·300 mm. Different strength rates were used while testing, but all up to 40% of the ultimate strength. European standard EN 1992-1-1 [12] prescribes the CC modulus of elasticity as a function of its compressive strength. The 28-day modulus of elasticity for quartzite aggregate is defined as follows:

$$E_{cm} = 22 \cdot \left(\frac{f_{cm}}{10}\right)^{0.3} \tag{14}$$

where:

$E_{cm}$ mean 28-day modulus of elasticity (GPa),

$f_{cm}$ mean 28-day compressive strength obtained on a cylinder sample (MPa).

Having in mind that the concrete elastic deformation is mostly influenced by the aggregate type, recommendations for the equation (14) modification are given in EN 1992-1-1 [12]:

- for limestone aggregates modulus should be reduced by 10%;
- for sandstone aggregates modulus should be reduced by 30%;
- for basalt aggregates modulus should be increased by 20%.

In order to evaluate this equation, studies with the experimental results of the CC and HVFAC modulus of elasticity were selected from the database [14], [42], [44], [48]–[50], [128], [129]. Figure 22 shows the relationship between the experimental compressive strength and the experimental modulus of elasticity of CC and HVFAC mixtures made with granite, limestone and sandstone aggregates.

As can be seen from Figure 22, similar power relationship type was observed for both HVFAC and CC but with weaker correlation and greater scatter presented in HVFAC mixtures.

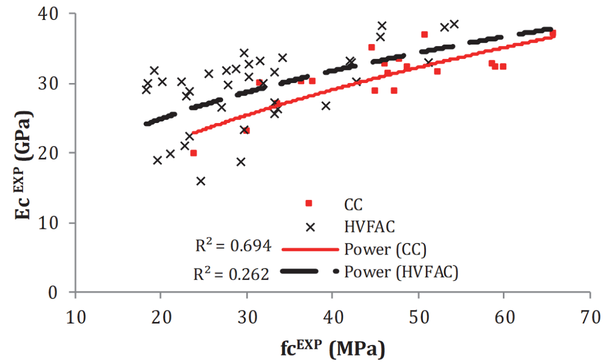



*Figure 22. Relationship between experimental values of 28-day modulus of elasticity and 28-day compressive strength for CC and HVFAC*

Yoon et al. [42] proposed the following modification of the EN 1992-1-1 [12] equation for the HVFAC modulus of elasticity:

- for HVFAC with 50% of FA in CM:

$$E_{cm} = (17 \pm 0.08) \cdot \left(\frac{f_{cm}}{10}\right)^{(0.45 \pm 0.10)} \tag{15}$$

- for HVFAC with 60% of FA in CM:

$$E_{cm} = (21.7 \pm 0.77) \cdot \left(\frac{f_{cm}}{10}\right)^{(0.29 \pm 0.08)} \tag{16}$$

The modulus of elasticity was calculated using the EN 1992-1-1 equation (14) for CC and HVFAC, considering different aggregate types and experimental cylinder 28-day compressive strength. Results are shown in Table 6 and Figure 23a as the calculated-to-experimental modulus ratio using descriptive statistical parameters.

The Yoon et al. proposal was evaluated for lower, average and upper values of proposed coefficients. For HVFAC mixtures with 45%-55% of FA in CM the modification proposed for 50% of FA and for HVFAC mixtures with 55%-65% of FA in CM the modification proposed for 60% of FA were used. Results are shown in Table 6 and Figure 23b as the calculated-to-experimental modulus ratio using descriptive statistical parameters.

*Table 6. Calculated-to-experimental 28-day modulus of elasticity ratio*

| | Sample No. | Mean Values | St. Deviation | CoV (%) | $LCL_{5\%}$* | $UCL_{95\%}$# |
|---|---|---|---|---|---|---|
| CC_EN 1992-1-1 | 22 | **1.07** | 0.21 | 19.10 | 0.74 | 1.41 |
| HVFAC_EN 1992-1-1 | 75 | **1.01** | 0.19 | 19.06 | 0.70 | 1.33 |
| Yoon et al_lower | 65 | **0.86** | 0.16 | 18.35 | 0.59 | 1.12 |
| Yoon et al_average | 65 | **0.99** | 0.18 | 18.21 | 0.70 | 1.29 |
| Yoon et al_upper | 65 | **1.13** | 0.20 | 17.75 | 0.79 | 1.46 |

*Lover confidence limit $LCL_{5\%}$ = Mean – 1.645 St.Dev.

#Upper confidence limit $UCL_{95\%}$ = Mean + 1.645 St.Dev.

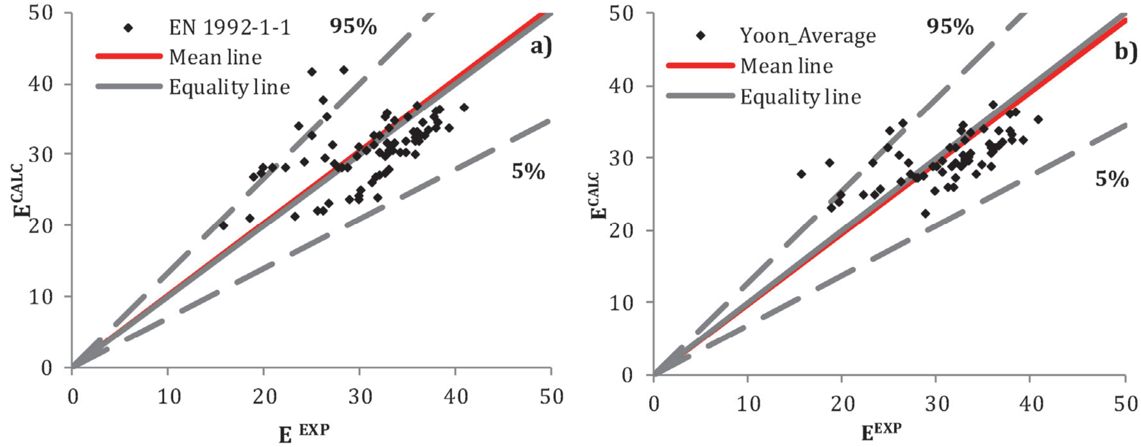



*Figure 23. Relationship between calculated and experimental values of HVFAC 28-day modulus of elasticity a) EN 1992-1-1 and b) Yoon et al. prediction*

Looking at Table 6, it can be seen that regarding statistical descriptors similar predictions were obtained using the EN 1992-1-1 equation and Yoon et al. (average) proposal, regardless of the FA/CM ratio. It was concluded that the EN 1992-1-1 equation (14) provided estimation of the HVFAC modulus of elasticity with similar accuracy and variation as for CC and that Yoon et al. (2014) prediction model brought no improvements.

The development of the modulus of elasticity over time for CC can be estimated using the equation given in EN 1992-1-1 as:

$$E_{cm}(t) = \left(\frac{f_{cm}(t)}{f_{cm}}\right)^{0.3} \cdot E_{cm} \quad \text{(GPa)} \qquad (17)$$

where:

$E_{cm}(t), f_{cm}(t)$ mean modulus of elasticity and mean compressive strength at the age t (GPa).

Chen et al. proposed the modification of the EN 1992-1-1 equation (17) as a function of the previously described coefficient C/(S+A) as follows:

In order to evaluate the application of equations (15) and (16) on the results from the database, studies with available experimental results of CC and HVFAC modulus of elasticity were selected at the age of 1, 3, 7, 14, 90, 180 and 365 days. The results are presented as the calculated-to-experimental modulus ratio for all ages in Table 7 using the descriptive statistical parameters. In all cases 28-day modulus of elasticity was calculated using equation (14) from experimental 28-day $f_{cm}$, as already concluded that it gave predictions of similar quality as for CC.

According to EN 1992-1-1, modulus of elasticity development over time is related to compressive strength development according to equation (17). Because of that, when calculating the HVFAC modulus of elasticity development according to this standard, Chen et al. proposal already recommended for compressive strength development was used (equation 10 for *s* coefficient). The graphical representation of the results is shown in Figures 24a and 24b.

Application of Chen et al. [126] proposal gave slightly better prediction of secant modulus of elasticity over time compared to EN 1992-1-1 proposal. On the basis of the evaluation on this database, it was concluded that Chen et al. prediction (equation 18) can be used for HVFAC with similar accuracy and variation of the results as for CC.

$$E_{cm}(t) = E_{cm} \cdot \beta_{cc}(t)^{0.3} = E_{cm} \cdot \left\{EXP\left[s \cdot \left(1 - \sqrt{\frac{28}{t}}\right) \cdot \left(-1.60 \cdot \frac{C}{S+A} + 5.26\right)\right]\right\}^{0.3} \quad \text{(GPa)} \qquad (18)$$

s coefficient defined in EN 1992-1-1 [12] in equation (9) depending on the cement type.

*Table 7. Calculated-to-experimental modulus of elasticity ratio at ages 1-365 days*

| | Sample No. | Mean Values | St. Deviation | CoV (%) | $LCL_{5\%}$* | $UCL_{95\%}$# |
|---|---|---|---|---|---|---|
| CC_EN 1992-1-1 | 22 | **1.00** | 0.22 | 22.15 | 0.64 | 1.36 |
| HVFAC_EN 1992-1-1 | 55 | **0.92** | 0.19 | 20.19 | 0.61 | 1.23 |
| Chen et al. | 55 | **0.94** | 0.20 | 21.46 | 0.61 | 1.28 |

*Lover confidence limit $LCL_{5\%}$ = Mean – 1.645 St.Dev.
#Upper confidence limit $UCL_{95\%}$ = Mean + 1.645 St.Dev.

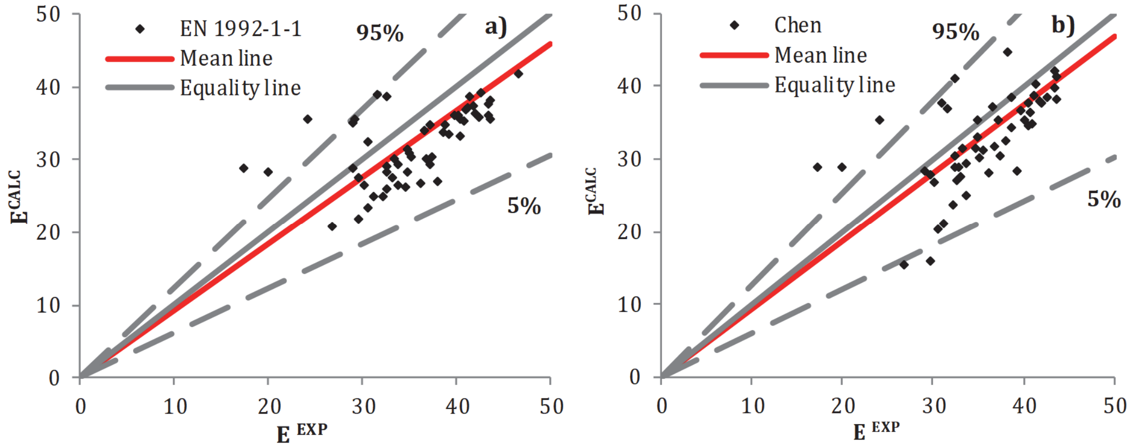



*Figure 24. Relationship between the calculated and experimental HVFAC modulus of elasticity at ages 1-365 days using a) EN 1992-1-1 b) Chen et al. [126] proposal*

## 6 Splitting tensile strength

Concrete tensile strength is an important parameter in both the serviceability and ultimate state verifications. It is used in stress analysis, the determination of crack width and spacing, deflection, minimum reinforcement, shear strength etc. European Standard EN 1992-1-1 defines the axial tensile strength of cement concrete in relation to the compressive strength as follows:

$$f_{ctm} = 0.3 \cdot \sqrt[3]{f_{ck}{}^{2}} \text{ (MPa) for compressive strength } f_{ck} \leq 50 \text{ MPa} \tag{19}$$

$$f_{ctm} = 2.12 \cdot \ln\left(1 + \frac{f_{ck}}{10}\right) \text{ (MPa) for compressive strength } f_{ck} > 50 \text{ MPa} \tag{20}$$

where:
$f_{ctm}$ mean axial tensile strength of concrete,
$f_{ck}$ characteristic compressive cylinder strength of concrete at 28 days ($f_{ck} = f_{cm} - 8$ MPa).

Axial tensile strength is rarely determined by testing, but it can be determined based on the splitting tensile strength using the equation given in EN 1992-1-1 [12] as follows:

$$f_{ct} = 0.9 \cdot f_{ct,sp} \quad \text{(MPa)} \tag{21}$$

where:
$f_{ct}$ axial tensile strength,
$f_{ct,sp}$ splitting tensile strength.

So, the splitting tensile strength can be determined using the combination of equations as:

$$f_{ct,sp} = \frac{1}{3} \cdot \sqrt[3]{f_{ck}{}^{2}} \text{ (MPa) for concrete classes } \leq C50/60 \tag{22}$$

$$f_{ct,sp} = \frac{2.12}{0.9} \cdot \ln\left(1 + \frac{f_{ck}}{10}\right) \text{ (MPa)} \tag{23}$$
for concrete classes $> C50/60$

In order to evaluate the application of these equations on the HVFAC tensile strength, concrete mixtures with available data regarding splitting tensile strength were selected from the database [8], [10], [47], [55], [56], [71], [83], [129], [130], [22]–[24], [26], [27], [43]–[45].

The relationship between the experimental 28-day compressive and splitting tensile strength for the selected HVFAC and CC mixtures is shown in Figure 25. As can be seen, the correlation between these two variables is higher for HVFAC mixtures compared with CC results but similar trend can be noticed indicating that the same power relationship type can be used to define them both. Slightly higher splitting tensile strengths for the same 28-day compressive strength can be noticed for CC mixtures compared with the HVFAC ones.

Splitting tensile strength was then calculated for the HVFAC and CC mixtures from the database using the EN 1992-1-1 equation (22 and 23). The results are presented in Table 8 as the calculated-to-experimental splitting tensile strength ratio using the descriptive statistical parameters. The experimental versus calculated splitting tensile strengths are also shown in Figure 26.

Although the prediction of HVFAC splitting tensile strength is slightly more conservative than for CC, it is recommended that the EN 1992-1-1 [12] equation (21) can be used to predict the HVFAC splitting tensile strength at this state-of-the knowledge. Other predictions regarding splitting tensile strength were not found in the literature.

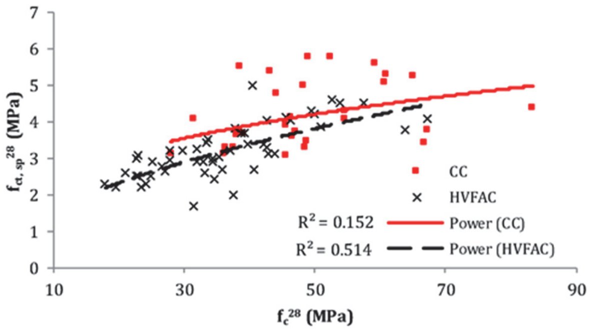



*Figure 25. Relationship between 28-day compressive and splitting tensile strength for CC and HVFAC*

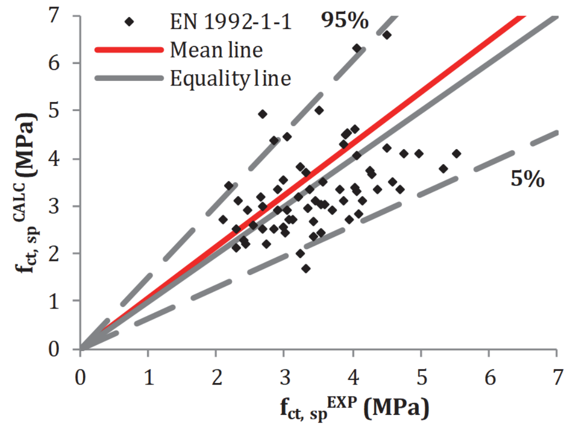



*Figure 26. Relationship between the calculated (EN 1992-1-1) and experimental 28-day HVFAC splitting tensile strength*

*Table 8. Calculated-to-experimental splitting tensile strength using EN 1992-1-1 prediction*

| | Sample No. | Mean Values | St. Deviation | CoV (%) | $LCL_{5\%}$* | $UCL_{95\%}$# |
|---|---|---|---|---|---|---|
| CC_EN 1992-1-1 | 20 | **0.94** | 0.19 | 20.02 | 0.63 | 1.26 |
| HVFAC_EN 1992-1-1 | 64 | **0.88** | 0.25 | 28.18 | 0.47 | 1.29 |

*Lover confidence limit $LCL_{5\%}$ = Mean – 1.645 St.Dev.
#Upper confidence limit $UCL_{95\%}$ = Mean + 1.645 St.Dev

## 7 Conclusions

The analysis of available experimental results of the HVFAC material properties showed that the extensive amount of research has been done so far. However, comprehensive analysis of HVFAC mechanical properties was not found in the literature, probably due to the great variety of FA physical and mechanical properties. Having that in mind, the database of 440 HVFAC and 151 CC mixtures collected from literature was made and analyzed. Database includes experimental results on the mechanical properties of HVFAC with class F fly ash and the amount of FA in CM in the range between 40% and 75%. Statistical analysis of the results in database enabled following conclusions:

The available empirical equations defined for CC can be used to predict the 28-day compressive strength of HVFAC based on its mixture proportions and using the FA efficiency factor.

The most important parameters influencing the FA efficiency are the amount of FA in CM, FA fineness and the FA and cement chemical composition.

Own proposal for FA efficiency (*k* factor value) as the function of FA chemical composition and its density showed good correlation with the experimental results. When HVFAC compressive strength was calculated using the Bolomey equation and own proposal for *k* factor value, the mean value of calculated-to-experimental compressive strength ratio was 1.02 with CoV of 24.5%.

The equation defined in EN 1992-1-1 for CC compressive strength development over time overestimates early age and underestimates later HVFAC compressive strengths.

The coefficient *s* influencing the compressive strength development over time proposed by Chen et al., in combination with EN 1992-1-1 equation for CC, can be used to predict the HVFAC compressive strength development.

The EN 1992-1-1 28-day modulus of elasticity prediction can be used to predict the HVFAC modulus of elasticity with similar accuracy and variation as for CC.

Chen et al. modification of EN 1992-1-1 equation for modulus of elasticity development over time can be used to predict the HVFAC modulus of elasticity with similar accuracy and variation as for CC.

The EN 1992-1-1 splitting tensile strength prediction can be used to predict the HVFAC splitting tensile strength with similar accuracy and variation as for CC.

These conclusions depend upon the database from which they were drawn and are valid only within the current range of parameters. Nevertheless, the database is freely accessible online which enables other researchers to update it, improve it, and analyse it in new and different ways compared with the ones presented in this study.

This work presented a leap forward on the road to HVAC practical application. Nevertheless, a variety of challenges regarding the use of FA in concrete still need to be overcome (heterogeneity of FA, durability of FA, behavior of structural elements made with HVFAC…).

The results and conclusions presented in this study give guidelines for practical HVFAC mix design procedure and prediction of basic mechanical properties. Greater use of HVFAC in applications where moderate compressive strength is needed could significantly reduce the amount of used cement and, therefore, the amount of emitted $CO_2$ compared with the traditional cement concrete. HVFAC would provide a sustainable solution to extensive growth in the construction sector and larger concrete consumption.

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**Technical Paper**

# Numerical parametric study on steel-concrete composite floor beams vibrations due to pedestrian traffic

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**ABSTRACT**

Human perception of floor vibrations and uncompromised serviceability of equipment are two most important acceptability criteria considering floor vibrations. While verification of deflection is a simple and well-known procedure in structures' design for serviceability limit state, the fulfilment of floor vibrations acceptability criteria are presented in different standards in the form of various calculation procedures. Results achieved through those calculation procedures are presented in the form of various classification of floor structures. Classification of composite floor structures due to vibrations is inconsistent considering different calculation procedures. Comparison of various calculation procedures for the definition of composite floor vibrations is presented in this paper. In addition, a parametric analysis is performed on the wide range of steel-concrete composite floor structures, through analysis of various composite floor layouts and a wide range of imposed loads values. The analysis of the relation between deflection, vertical vibrations and accelerations of steel-concrete composite floor beams is presented in this paper. The results of the parametric analysis are given through direct relation between deflections of composite beams and achieved floor class for the fulfilment of vibrations acceptability criteria due to the pedestrian walking.

## 1 Introduction

Pedestrian traffic is the most common internal source of floor vibrations, resulting in vertical oscillatory movement of structure parts with certain amplitude and frequency. On the other hand, wind actions, road and rail traffic, seismic actions and impact on the structure members, are the most common external source of structure vibrations. Vibrations are mostly vertical or horizontal. While seismic and wind actions result in horizontal vibrations of structures, walking of pedestrians is the most usual source of vertical vibrations.

Two most important acceptability criteria of floor vibrations are human perception and uncompromised serviceability of equipment for different floor occupancies. Human response to floor motion is a very complex phenomenon and it is often related to the combination of different factors such as the magnitude of motion, the surrounding environment and the type of human activity which takes place at that moment. Although the vibrations of a floor structure can cause a feeling of uncertainty and significantly decrease human comfort and quality of life inside the building, their occurrence does not necessarily lead to less structure safety.

Various floor occupancies inside of buildings, such as hospitals, surgeries, schools, laboratories, offices, residential buildings, hotels or sport and industry facilities require different acceptability criteria of floor vibrations. Increased floor vibrations can compromise the building functionality and operation of the equipment inside the building, which further emphasizes the importance of acceptance criteria definition at the early stage of structure design. Improvement of an existing structure to reduce its susceptibility to vibrations is a very difficult and expensive process that requires significant modifications of structure mass, stiffness or increase of structure damping, often using special devices.

The first step in structure dynamic analysis is modelling dynamic loads induced by human activities and subsequent determination of acceptance criteria of floor vibrations. These loads can be separated in two groups: periodic dynamic loads induced by rhythmic body motion such as walking, running, dancing and stochastic dynamic loads

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induced by single body motions such as heel impact, jumping off impact or landing impact after jumping from an elevated position [1]. The dynamic loads of one or more pedestrians vary with time and position and can be classified as impulsive loads (usually in situ loads) caused by persons who jump from the objects or sudden standing of a crowd and periodic (moving loads) caused by walking, marching or running [2], [3].

Appearance and magnitude of floor structure vibrations depend on type and layout of vertical and horizontal constructive elements, the arrangement of interior walls and type of floor structures, suspended ceilings and floor finishing. Aforementioned characteristics of the building structure affect not only the natural frequencies of different fundamental mode shapes but also structural damping ratio which present important characteristic for dynamic analysis of the structure. In addition, analysis of floor structure vibrations becomes more complicated considering the nature of dynamic excitation caused by pedestrian traffic. In common engineering practice, the complexity of floor structures vibrations caused by pedestrian traffic is explained through simplified design procedures in which continuous structural systems are replaced with discrete systems with a single degree of freedom and the complex function of pedestrian walk is broken down into a series of sinusoidal functions based on the Fourier transformation. These simplified design procedures are given in different standards, technical guidelines and design recommendations [1], [3], [4], [6] - [8].

The description of the dynamic loads generated by pedestrian traffic is not a simple task. Numerous investigations were made aiming to establish parameters to describe such dynamic actions. The vertical accelerations of the body mass are associated with reactions on the floor and they are closely periodic, at the pace frequency [6]. This dynamic loading model is most commonly represented by the load static parcel, related to the individual's weight, and combination of harmonic forces with frequencies that are multiples or harmonics of the basic frequency of the force repetition [2], [4], [6], [8]. For the analysis of the dynamic performance of composite steel-concrete floors, different authors developed various dynamic load models of pedestrian traffic [9], [10], [11].

The latest research significantly moves towards a more realistic estimation of the vibration response through new design methods to account the variability of each pedestrian, their interaction and statistical evaluation of obtained results. In addition, the latest researches highlighted the importance of human structure interaction, i.e. the effects of the human body on the dynamic properties of the occupied structure [12], [13]. The new modelling approach describes a human body as a mechanical system often composed of masses connected with springs and dampers. These new modelling approaches are more complex and lead to the more realistic prediction of structure vibration response, but it remains to be seen how they will be reflected on the simplified design procedures given in aforementioned design guidelines and how they can be used in common design procedures.

Determination of dynamic properties of floor structures, such as natural frequency, modal mass and damping of the structure is important for the definition of acceptable levels of floor vibrations. The fundamental natural frequency of floor structures can be defined using simplified design procedures given in different literature [4], [8], [14], [15], [16] or using FEM analysis in the appropriate software.

Design recommendations for structures considering fulfilment of vibrations acceptance criteria can be found in different standards, design manuals and other specialized literature. Historically, many designers considered that fundamental natural frequency is the main structure characteristic and that sufficiently high fundamental natural frequency provides appropriate performance of the structure due to floor vibrations [4]. According to Eurocode, serviceability criteria for floor vibrations should be considered for each project or should be defined within National Annex. According to EN 1990, Annex A1 [17] a comfort of user and functionality of structure or its structural members should be considered in order to display acceptable behaviour regarding vibrations of floor structures. In addition, EN 1990 [17] defines that for the further guidance EN 1991-1-1 [18], EN 1991-1-4 [19] and ISO 10137 [3] should be used. EN 1990, Annex A2 [17] gives recommended maximum values for accelerations of any part of the floor structures as 0.7 m/s$^2$ for vertical vibrations and 0.2 m/s$^2$ for horizontal vibrations. ISO 2631-2 [5] defines acceptability criteria of floor vibrations in the function of human perceptibility curves for various floor accelerations. The same acceptability criteria are also adopted in BS 6472-1 [20] through base acceptability curves and multiplying factors $R$ of different floor occupancies for horizontal and vertical vibrations. New design recommendations for acceptability criteria of composite steel-concrete floors exposed to vibrations induced by human activities are defined based on the results of the extensive investigation within ECCS (research project JRC55118 [15]). Three main parameters that influence the floor vibrations are fundamental natural frequency $f_0$, structural damping $D$ and modal mass $M_{mod}$. Determination of $OS\text{-}RMS_{90}$ variable is a part of the general procedure for the determination of acceptable floor response to excitation induced by walking persons. Variable *OS-RMS* represents the root mean square velocity for significant one step, which is associated with a certain probability of body mass and step frequency. Variable $OS\text{-}RMS_{90}$ is introduced in the purpose of comfort estimation and definition of vibrations acceptance criteria presenting velocity (or acceleration) for a significant single step that is larger than 90% fractile of people walking steps. This variable is defined as a single representative response parameter and is suitable for being compared with response requirements depending on the type of building and its use, according to JRC55118 [15]. The direct relation between two different variables given in BS 6472-1 [20] and JRC55118 [15] (multiplying factor $R$ and $OS\text{-}RMS_{90}$ variable, respectively) is defined through $OS\text{-}RMS_{90}$ equivalent given in JRC55118 [15].

Current design recommendations for floor vibrations recognize peak or root mean square accelerations as main criteria for fulfilment of acceptability demands, as explained previously. However, it was shown that this procedure can be complex for the usual engineering practice. Therefore, the definition of the direct relation between composite beam deflection and achieved floor class for the fulfilment of vibrations acceptability criteria could facilitate the design procedure. Firstly, the numerical analysis of composite steel-concrete beams and floor structures with the dynamic model of pedestrian loading is presented in this paper. In this framework, the difference of the acceptability criteria achieved using simplified design procedures given in BS 6472-1 [20] and JRC55118 [15] and through numerical analysis performed in Sofistik FE software (see https://www.sofistik.com [21]) is shown. Afterwards, the parametric study of composite steel-concrete beams is presented in this framework. The relationship between the overall deflections of composite beam and vibrations acceptability criteria for different floor occupancies according to JRC55118 [15] is presented as a result of the parametric study.

## 2 Classification of composite floor structures based on numerical analysis

### 2.1 Geometrical properties and natural frequencies

In this framework, vertical vibrations assessment of composite steel-concrete beams and their comparison with acceptance levels given in BS 6472-1 [20] and JRC55118 [15] is performed for six composite beams with 8, 10, 12 and 15 m span and 4 m spacing between beams, denoted from CB 1 to CB 4. The shape and dimensions of profiled steel sheeting, composite concrete slab, headed studs and structural steel with mechanical properties of adopted materials are shown in Figure 1 and Table 1.

Composite steel-concrete beams are made with standard hot-rolled steel sections and composite slab with profiled steel sheeting CF70. The direction of profiling (perpendicular to the beam axis) and detailed dimensions of profiled steel sheeting with 1 mm thickness are shown in Figure 1a. The total height of the composite slab is 150 mm with concrete C30/37. Steel sections and profiled steel sheeting are made from steel grade S235 and S355, respectively. Composite action between the steel beam and composite slab is achieved with headed studs - 22 mm in diameter and 120 mm height.

Composite beams CB 2-1 and CB 3-1 are variant solutions of composite beams CB 2 and CB 3 with larger structural steel cross-section and up to four times higher second moment of area of composite beam cross-section. Numerical models of composite beams are developed in Sofistik FE software [21]. The calculated second moment of area of composite beams cross-sections and those obtained

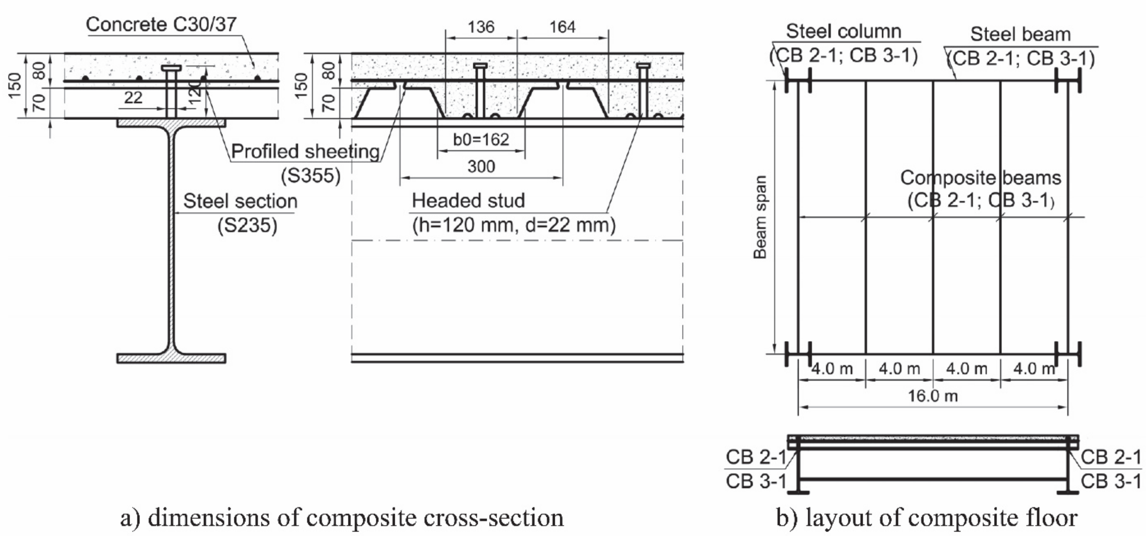



*Figure 1. Layout and geometry of composite beam and floor*

*Table 1. Cross-section properties of composite beams*

| Beam | Steel section | Span (m) | Second moment of area of composite slab ($cm^4$/m) | Second moment of area of composite beam ($cm^4$) | Second moment of area of composite beam - Sofistik ($cm^4$) | Difference (%) |
|---|---|---|---|---|---|---|
| CB 1 | IPE 360 | 8.0 | 881 | 71980 | 71990 | 0.01 |
| CB 2 | IPE 450 | 10.0 | | 130723 | 130700 | 0.02 |
| CB 2-1 | HEA 600 | 10.0 | | 387122 | 387100 | 0.01 |
| CB 3 | IPE 550 | 12.0 | | 232923 | 233300 | 0.16 |
| CB 3-1 | HEB 800 | 12.0 | | 877235 | 877200 | 0.00 |
| CB 4 | IPE 600 | 15.0 | | 313391 | 313400 | 0.00 |

from Sofistik FE software [21] are shown in Table 1. It can be seen that close agreement was achieved between individual parameters with a difference of less than 1 %. This difference is the consequence of concrete volume embedded in profiled steel sheeting which is modelled in Sofistik FE software [21] as a concrete part of the cross-section with the reduced modulus of elasticity and height which represent the height of profiled steel sheeting. However, this difference is taken as a small calculation error which is common for software analysis and satisfactory small for further numerical analysis.

Loads adopted for all numerical examples are 5.0 kN/m$^2$ of imposed load, 0.75 kN/m$^2$ of loads during construction and 1.0 kN/m$^2$ of floor finishing and installations. Calculation of ultimate and serviceability limit states is performed according to recommendations given in EN 1994-1-1 [22]. Composite beams are designed as unpropped during construction, except floor beam with 15 m span which is calculated as propped beam during construction in a third of the span. For all analysed composite beams, precamber of the steel section is predicted for the value of beam vertical deflection which is reached before composite action is envisaged. Adopted structural damping for all analysed composite beams is 3 % as total damping which consists of structural damping, damping due to furniture and damping due to finishes, according to JRC55118 [15]. The fundamental natural frequency of composite beams is calculated using the self-weight approach [20], as shown in Eq.1:

$$f_0 = \frac{17.8}{\sqrt{\delta_\mathrm{m}}} \tag{1}$$

$$\delta_\mathrm{m} = \frac{5}{384}\left(\frac{q_\mathrm{swb}L^4}{E_\mathrm{a}I_\mathrm{i0}}\right) \tag{2}$$

where $L$ is the composite beam span; $\delta_\mathrm{m}$ vertical deflection of the composite beam in millimetres (mm); $q_\mathrm{swb}$ is the composite beam weight per unit length (kN/m); $E_\mathrm{a}$ is the modulus of elasticity of structural steel and $I_\mathrm{i0}$ is the second moment of area of composite cross-section. In addition, the fundamental natural frequency of composite floor structure, composed of composite beams with arrangement presented in Figure 1b, is determined for orthotropic floor structure [14], using Eq.3, Eq.4 and Eq.5, respectively:

$$\frac{1}{f_0^2} = \frac{1}{f_\mathrm{0s}^2} + \frac{1}{f_\mathrm{0b}^2} \tag{3}$$

$$f_\mathrm{0s} = 3.56\sqrt{\frac{E_\mathrm{a}I_\mathrm{s}}{m_\mathrm{s}b^4}} \tag{4}$$

$$f_\mathrm{0b} = \frac{\pi}{2}\sqrt{\frac{E_\mathrm{a}I_\mathrm{i0}}{m_\mathrm{b}bL^4}} \tag{5}$$

where $f_0$, $f_\mathrm{0b}$ and $f_\mathrm{0s}$ are fundamental natural frequencies of the composite floor, composite beam and composite slab, respectively; $m_\mathrm{s}$ and $m_\mathrm{b}$ is the composite slab and beam vibrating mass per unit area (kg/m$^2$) respectively [14]; $I_\mathrm{s}$ is the second moment of area of the composite slab; $b$ is the spacing between composite beams and other variables which have the same definition as in the Eq.1 and Eq.2. In addition, 10% of imposed loads were used for determination of natural frequencies based on two different approaches, [15] and [20]. Determination of composite floor fundamental natural frequency $f_0$ using Eq.3 is based on Dunkerley's approach [15]. Based on the Dunkerley's approach, expected mode shape of the composite floor is divided into two independent single-mode shapes, composite slab and composite beam mode shape, with their natural frequencies. This approach is used when expected mode shape is complex and estimates its lower natural frequency limit. In addition, in Eq.4 and Eq.5 coefficient 3.56 and π/2 are used for simple supports and both fixed supports against rotation, respectively and values for other end conditions are given by Wyatt [6]. Eq. (1) and (5) are derived from the same equation and represent fundamental natural frequency for simply supported beams. Eq. (1) gives satisfactory results for beams when analysed alone. Dunkerley's approach presented in Eq. (3) to (5) is used for the whole composite floor. Moreover, the fundamental natural frequency of analysed composite beams and composite floors is calculated in Sofistik FE software [21]. Results of natural frequencies calculation using different approaches and their comparison with the results of numerical analysis in Sofistik FE software [21] are presented in Table 2.

Minimal utilization level of plastic resistance moment of the composite cross-section for beams CB 1, 2, 3 and 4 is 75 %. The same utilization level for composite beams CB 2-1 and CB 3-1 is approximately 35 %, considering that these beams are the variant solution with larger structural steel cross-sections. The results presented in Table 2 indicate that difference between natural frequencies of composite beam and orthotropic floor structure for composite beams CB 1, 2, 3 and 4 with higher utilization level is less than 10 %. Lowering the level of utilization with larger structural steel cross sections for composite beams CB 2-1 and CB 3-1 resulted in a higher difference between natural frequencies for two individual calculation procedures, which approximately amounts 20 %. This is attributed to the higher fundamental natural frequency of composite beams CB 2-1 and CB 3-1 which exceeds 7 Hz, calculated according to self-weight approach [20] due to lower vertical deflection $\delta_\mathrm{m}$. Composite beams CB 1, 2, 3 and 4 which have fundamental natural frequency lower than 7 Hz are classified as beams with low frequency according to BS 6472-1 [20]. Their natural frequency show close agreement with the frequency of the same orthotropic floor structure.

*Table 2. Fundamental natural frequency of composite beam and floor*

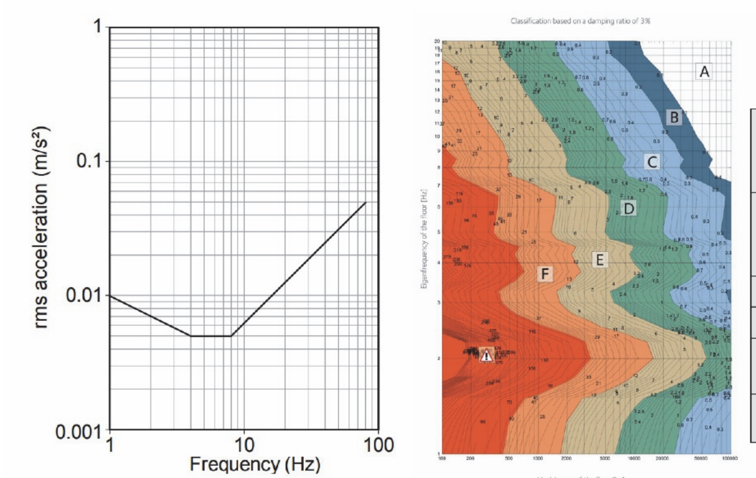
| Beam | Self-weight approach - composite beam [20] | | | Orthotropic floor structure (steel beam + concrete slab) [15] | | | | | Sofistik [21] Beam | Sofistik [21] Floor |
|---|---|---|---|---|---|---|---|---|---|---|
| | $q_{swb}$ (kN/m) | $\delta_m$ (mm) | $f_{0b}$ (Hz) | $m_s$ (kg/m²) | $m_b$ (kg/m²) | $f_{0s}$ (Hz) | $f_{0b}$ (Hz) | $f_0$ (Hz) | $f_{0b}$ (Hz) | $f_0$ (Hz) |
| CB 1 | 19.51 | 8.13 | 6.24 | 482.67 | 497.22 | 13.78 | 6.23 | 5.67 | 6.11 | 5.67 |
| CB 2 | 19.72 | 10.86 | 5.40 | | 502.45 | | 5.39 | 5.02 | 5.26 | 5.16 |
| CB 2-1 | 20.72 | 3.88 | 9.04 | | 528.03 | | 9.02 | 7.54 | 8.67 | 7.50 |
| CB 3 | 20.00 | 12.68 | 5.00 | | 509.68 | | 4.99 | 4.69 | 4.84 | 4.78 |
| CB 3-1 | 21.56 | 3.66 | 9.31 | | 549.44 | | 9.29 | 7.70 | 8.85 | 7.98 |
| CB 4 | 20.16 | 23.00 | 3.71 | | 513.76 | | 3.70 | 3.58 | 3.60 | 3.51 |

Numerical models are developed in Sofistik FE software [21] in order to compare natural frequencies obtained from the software with those obtained from the literature. Numerical models for composite beams are developed using beam structural element with composite cross-section, which is defined for every composite beam with belonging effective width. Dimensions of the composite cross-section are given in Figure 1a. Concrete volume embedded in profiled steel sheeting is modelled in Sofistik FE software [21] as a concrete part of the cross-section with the reduced modulus of elasticity and reduced self-weight in order to represent real self-weight of the composite beam. All analysed composite beams are simply supported. Numerical models for composite floor structure are developed using composite beams with cross-sections and spans defined in Table 1. The composite slab is defined with equivalent height in order to realistically present composite cross-section, shown in Figure 1a. The concrete plate is connected to steel beams with rigid links, defining the one-way composite slab. The general layout of composite floor structure is presented in Figure 1b. All composite beams (primary beams) are connected to steel beams (secondary beams) and columns with simple joints. The analysed composite beam (primary beam) / steel beam (secondary beams) span ratio is between 1.0 and 1.5 (1.0 for CB 1, 1.25 for CB 2 and CB 4 and 1.5 for CB 3). Solid finite elements are used for numerical analysis of composite floor structure in Sofistik FE software [21].

Natural frequency in Sofistik FE software [21] is calculated including structure self-weight with floor finishing and installations and 10% of imposed loads, according to recommendations given in JRC55118 [15]. As shown in Table 2, close agreement between natural frequencies of developed numerical models obtained from software and recommendations given in BS 6472-1 [20] and JRC55118 [15] is achieved.

## 2.2 Vibrations of composite floor structures induced by pedestrian loading

Figure 2 presents acceptance levels diagrams of floor vibrations according to BS 6472-1 [20] and JRC55118 [15] and their comparison through the direct relationship between multiplying factor *R* and *OS-RMS*$_{90}$ equivalent. BS 6472-1 [20] defines acceptance levels of floor vibrations for different floor occupancies in the form of the base curve shown in Figure 2a and multiplying factors *R*, as shown in Figure 2c.




a) base curve for vertical accelerations [20]

b) classification of floor response [15]

| Intended use of the structure | Multiplying factor *R* | *OS-RMS*$_{90}$ equivalent |
|---|---|---|
| Critical working area | 1 | 0.1 |
| Residential | 2 to 4 | 0.2 to 0.4 |
| Quiet office | 2 | 0.2 |
| General office | 4 | 0.4 |
| Workshops | 8 | 0.8 |

c) vibration limits specified in [3], [20] and equivalent *OS-RMS*$_{90}$ [15]

*Figure 2. Floor vibrations acceptance criteria*

Multiplying factor $R$ can be calculated using Eq.6 for structures with fundamental natural frequency lower than 7 Hz:

$$R = \frac{68000 C_f}{m_b S_{eff} L \zeta} \tag{6}$$

$$S_{eff} = 4.5 \left( \frac{E_a I_s}{m_b f_0^2} \right)^{\frac{1}{4}} \tag{7}$$

where $C_f$ is the coefficient which depends upon the natural frequency and should be adopted as 0.4 if $f_0$ is between 3 Hz and 4 Hz, as 0.2 if $f_0$ is higher than 4.8 Hz or should be calculated as 1.4-0.25*$f_0$ if $f_0$ is between 4 Hz and 4.8 Hz, as defined in BS 6472-1 [20]; $\zeta$ is the structure damping ratio; $S_{eff}$ is composite floor effective width (m) [6] and other variables have the same definition as in previous equations. Fourier component factor $C_f$ should be taken as a function of the floor fundamental natural frequency but is also related to the type of excitation. Precise recommendations for values of coefficient $C_f$ for fundamental natural frequency lower than 3 Hz are not given in current literature. Therefore, it can be concluded that the nature of excitation of vertical accelerations does not significantly influence the structure response and adoption of value 0.4 for this coefficient gives safe side prediction. Multiplying factor $R$ can be calculated using Eq.8 for structures with the fundamental natural frequency which exceeds 7 Hz:

$$R = \frac{30000}{m_b b_e L} \tag{8}$$

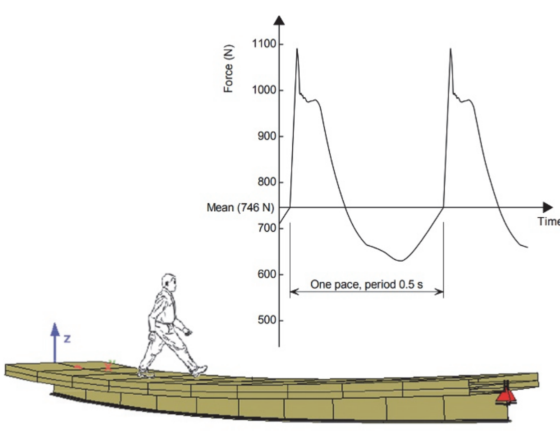
$$b_e = \min(b, 40 h_p) \tag{9}$$

where $h_p$ is the height of concrete slab and other variables have the same definition as in previous equations.

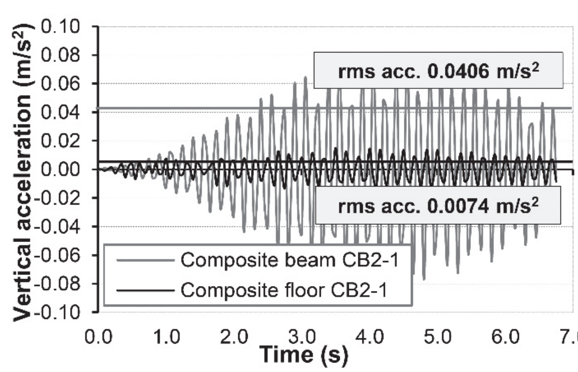
Multiplying factors $R$ calculated according to Eq.6 and Eq.8 based on natural frequencies given in Table 2 are presented in Table 3. Calculated multiplying factors $R$ for all numerical examples are used for drawing new acceptability curves based on the Figure 2a and calculation of root mean square accelerations $a_{rms}$ for certain fundamental natural frequency. These results are also presented in Table 3.

*Table 3. Acceptance levels according to BS 6472-1 [20]*

| Beam | Self-weight approach [20] | | | | | | Sofistik [21] | |
|---|---|---|---|---|---|---|---|---|
| | Composite beam | | | Orthotropic floor | | | Beam | Floor |
| | $C_f$ | $R$ | $a_{rms}$ (m/s$^2$) | $C_f$ | $R$ | $a_{rms}$ (m/s$^2$) | $a_{rms}$ (m/s$^2$) | $a_{rms}$ (m/s$^2$) |
| CB 1 | 0.20 | 7.724 | 0.03862 | 0.20 | 7.724 | 0.03862 | 0.01167 | 0.00431 |
| CB 2 | 0.20 | 5.765 | 0.02883 | 0.20 | 5.765 | 0.02883 | 0.01136 | 0.00221 |
| CB 2-1 | 0.20 | 1.810 | 0.00905 | 0.20 | 1.775 | 0.00888 | 0.04062 | 0.00738 |
| CB 3 | 0.20 | 4.681 | 0.02341 | 0.23 | 4.687 | 0.02344 | 0.01688 | 0.00285 |
| CB 3-1 | 0.20 | 1.449 | 0.00725 | 0.20 | 1.422 | 0.00711 | 0.02489 | 0.00559 |
| CB 4 | 0.40 | 6.381 | 0.03191 | 0.40 | 6.503 | 0.03252 | 0.00885 | 0.00907 |




a) numerical model of pedestrian loading according to Bachmann [1]




b) vertical accelerations of composite beam and floor CB2-1

*Figure 3. Numerical analysis in Sofistik FE software [21]*

To calculate structure vertical acceleration due to pedestrian loading, dynamic analysis is performed in Sofistik FE software [21]. Dynamic load function for continuous excitation due to pedestrian traffic is shown in Figure 3a, and explained in detail in numerous publications [1], [4], [6]. Figure 3a presents contact force from a single footfall and basic pace frequency is presented with the second Fourier component [6]. This type of dynamic loading can be broken down into a series of sinusoidal functions based on Fourier transformation. Fourier transformation for dynamic load function of human walking is explained also in [23] and short review of dynamic load factors for each harmonic and different type of human activities is given in [24].

The numerical model of pedestrian traffic is analysed in Sofistik FE software [21], using DYNA module for dynamic analysis which is incorporated in this software. Sofistik FE software [21] offers direct implementation of pedestrian traffic according to Bachmann [1], which function is presented in Figure 3a. Using DYNA module for dynamic analysis pedestrian traffic is implemented with a total weight of one person of 800 N, which is moving over composite beams or composite floor structures with pacing width of 0.7 m and pace frequency of 2.10 Hz. Results of numerical analysis performed in Sofistik FE software [21] in the form of root mean square vertical accelerations in the middle of the beam span are given in Table 3. Root mean square accelerations are calculated based on the accelerations of the beam in the middle of the span (Figure 3b) obtained through dynamic analysis in Sofistik FE software [21]. The results shown in Table 3 indicate that numerical model of composite beams CB 2-1 and CB 3-1 gives higher values of root mean square accelerations $a_{rms}$ in comparison with the same values obtained from multiplying factor $R$ and base curve, but the close agreement between two parameters for the same composite floor structure. These results also indicate that FE analysis of composite beams with a fundamental natural frequency lower than 7 Hz gives sufficiently accurate results, excluding the necessity for modelling of the whole composite floor structure. However, this approach could not be adopted for composite beams with a fundamental natural frequency higher than 7 Hz. Their behaviour can be observed only through the numerical model of the whole composite floor structure. In addition, vertical accelerations obtained from numerical analysis for composite beams CB 1, 2, 3 and 4 and all composite floor structures have lower values in comparison with the same values obtained from literature, as shown in Table 3.

Classification of analysed composite floor structures according to recommendations given in JRC55118 [15] is shown in Table 4. Graphical presentation of floor classification for adopted natural damping of 3 % is shown in Figure 2b. To define composite floor class it is necessary to define its fundamental natural frequency and modal mass using Eq. 3 and Eq. 10, respectively:

$$M_{\text{mod}} = M_{\text{total}}\left(\frac{\delta_{\text{x}}^2+\delta_{\text{y}}^2}{2\delta^2}+\frac{8}{\pi^2}\frac{\delta_{\text{x}}\delta_{\text{y}}}{\delta_{\text{total}}^2}\right) \tag{10}$$

$$\delta_{\text{x}} = \frac{5}{384}\left(\frac{m_{\text{s}}gb^4}{E_{\text{a}}I_{\text{s}}}\right) \tag{11}$$

$$\delta_{\text{y}} = \frac{5}{384}\left(\frac{m_{\text{b}}gbL^4}{E_{\text{a}}I_{\text{i0}}}\right) \tag{12}$$

where $\delta_x$ is the vertical deflection of a composite slab, as defined in Eq.2; $\delta_y$ is the vertical deflection of the composite beam; $\delta_{total}$ is the sum of vertical deflections of composite beam and composite slab and other variables have the same definition as in previous equations.

*Table 4. Acceptance levels according to JRC55118 [15]*

| Beam | Orthotropic floor structure (steel beam + concrete slab) [15] | | | | | | | Sofistik [21] | |
|---|---|---|---|---|---|---|---|---|---|
| | $\delta_y$ (mm) | $\delta_x$ (mm) | $\delta_{total}$ (mm) | $M_{mod}$ (kg) | Class | *OS-RMS<sub></sub>*$_{90}$ *equivalent* | *R* | Beam Class | Floor Class |
| CB 1 | 8.128 | 8.531 | 16.659 | 7202.5 | D | 0.8 | 8.000 | C | A |
| CB 2 | 10.859 | | 19.309 | 9110.9 | D | 0.8 | 8.000 | C | A |
| CB 2-1 | 3.877 | | 12.408 | 9701.1 | C | 0.2 | 2.000 | D | B |
| CB 3 | 12.683 | | 21.214 | 11118.2 | D | 0.8 | 8.000 | C | A |
| CB 3-1 | 3.655 | | 12.186 | 12137.6 | C | 0.2 | 2.000 | C | B |
| CB 4 | 23.003 | | 31.534 | 14260.5 | D | 0.8 | 8.000 | B | A |

Class A – recommended for all floor occupancies;
Class B – critical for critical areas and recommended for all other occupancies;
Class C – not recommended for critical areas and recommended for all other occupancies;
Class D – not recommended for critical areas, critical for use in hospitals, surgeries, schools and training centres, recommended for all other occupancies;
Class E – not recommended for critical areas, hospitals, surgeries, schools and training centres, critical for residential buildings, office buildings, meeting rooms, senior citizens residential buildings and hotels, recommended only for industrial workshops and sports facilities;
Class F – critical for industrial workshops and sports facilities and not recommended for any other floor occupancies.

Classification of the composite floor structure is later used for definition of *OS-RMS*$_{90}$ coefficient, according to JRC55118 [15] and determination of multiplying factor *R*. As shown in Table 4, multiplying factor *R* which is determined based on the *OS-RMS*$_{90}$ equivalent shows good agreement with the same values presented in Table 3. Moreover, results of numerical analysis in Sofistik FE software [21] are used for determination of multiplying factor *R* and *OS-RMS*$_{90}$ equivalent in order to define the relationship between root mean square accelerations obtained from numerical analysis and floor structure classification given in JRC55118 [15]. In addition, results given in Table 3 indicate that detail numerical analysis of pedestrian loading in FE software gives lower vertical accelerations and lower class of the floor structure in comparison with the results obtained from design recommendations given in JRC55118 [15].

Lower vertical accelerations and lower floor structure class provide that considered floor structure can be used for a wider range of floor occupancies. As defined in JRC55118 [15] and presented in Table 4, floor structure can be classified from A (recommended for usage for different occupancies from critical areas and hospitals to the sports facilities) to F (critical for usage for industrial workshops and sports facilities and not recommended for other occupancies).

### 2.3 Discussion of numerical analysis results

According to the results of numerical analysis, the following remarks can be stated:

1) BS 6472-1 [20] and JRC55118 [15] provide a relatively simple calculation procedure of composite floor vibrations. In addition, the results obtained from two individual design procedures show good agreement (see Table 3 and Table 4). Moreover, JRC55118 [15] defines the relationship between multiplying factor *R* given in BS 6472-1 [20] and similar *OS-RMS*$_{90}$ factor used for classification of composite floor structures. JRC55118 [15] gives more detail partitioning between floor occupancies than BS 6472-1 [20], which can be helpful for structure design.

2) Numerical analysis of composite beams in FE software with a fundamental natural frequency higher than 7 Hz gives inappropriate results. Root mean square accelerations for these beams obtained from FE software have higher values than the same values obtained from BS 6472-1 [20] (see Table 3). In addition, numerical analysis of composite floor structures gives lower values of floor accelerations.

3) Accelerations of composite beams and floor structures which are the result of numerical analysis are lower than the same results obtained using the design recommendations given in BS 6472-1 [20] and JRC55118 [15]. Lower accelerations of floor structures are more favourable and enable the usage of these structures for a wider range of floor occupancies. In addition, detail numerical analysis of floor vibrations is of high importance for the design of complex structures or structures occupied with high precision equipment or specific working processes.

## 3 Parametric study of vibrations of composite steel-concrete beams

### 3.1 Analysis method

Parametric study of vibrations of composite steel-concrete beams, which is presented in this chapter is conducted using design recommendations for ultimate and serviceability limit state given in EN 1994-1-1 [22] and JRC55118 [15]. The aim of the parametric study was to define the relationship between vibrations of composite beams and their deflection. While verification of deflection is a well known and relatively simple procedure, calculation of floor vibrations caused by pedestrian traffic is defined in different literature and still causes certain design difficulties. In addition, meeting the requirements of floor vibrations is directly related to the envisaged floor occupancies. Classification of composite floor structures due to vibrations according to JRC55118 [15], which is shown in the previous chapter, is used in this parametric study. The parametric study included composite beams with span from 7 m to 15 m and span of the composite slab (spacing between composite beams) which is analysed is 3 m and 4 m. Composite beams are performed with three types of hot-rolled steel sections (IPE, HEA and HEB). The main properties of composite floor structures analysed in this parametric study are given in Table 5. Three main composite structure types (CS 1, CS 2, CS 3) are analysed with 0.75 kN/m$^2$ of loads during construction and for imposed load from 2.0 to 5.0 kN/m$^2$ which comprise a wide range of floor occupancies according to JRC55118 [15] and EN 1991-1-1 [18]. Composite structures CS 1 and CS 3 are analysed for 2.0 kN/m$^2$ and CS 2 for 1.0 kN/m$^2$ of additional permanent load due to floor

*Table 5. Analysis parameters*

<table>
<tr><th rowspan="3"></th><th colspan="4">Composite floor</th><th></th><th colspan="3">Load (kN/m$^2$)</th></tr>
<tr><th rowspan="2">Span (m)</th><th colspan="3">Profiled steel sheeting</th><th rowspan="2">Second moment of area of composite slab (cm$^4$/m)</th><th rowspan="2">During construction</th><th rowspan="2">Additional permanent</th><th rowspan="2">Imposed</th></tr>
<tr><th>Thickness (mm)</th><th>Height (mm)</th><th>Concrete height (mm)</th></tr>
<tr><td>CS 1</td><td>3.0</td><td>1.20</td><td>60</td><td>60</td><td>562</td><td rowspan="6">0.75</td><td>2.0</td><td>2.0 – 5.0</td></tr>
<tr><td>CS 2</td><td>4.0</td><td>1.00</td><td>70</td><td>80</td><td>881</td><td>1.0</td><td>2.0 – 5.0</td></tr>
<tr><td rowspan="4">CS 3</td><td rowspan="4">4.0</td><td rowspan="4">1.20</td><td rowspan="4">80</td><td>60</td><td>784</td><td rowspan="4">2.0</td><td>2.0</td></tr>
<tr><td>70</td><td>944</td><td>3.0</td></tr>
<tr><td>80</td><td>1127</td><td>4.0</td></tr>
<tr><td>90</td><td>1333</td><td>5.0</td></tr>
<tr><td colspan="9">Adopted material properties in the parametric study: structural steel - S235, concrete class - C30/37, reinforcement - B500, profiled steel sheeting - S355.</td></tr>
</table>

finishing and installations. Every composite structure is analysed for each value of imposed load with three types of hot-rolled steel sections IPE, HEA and HEB. Therefore, the presented parametric study included 324 composite beams overall.

The same design procedure was performed for every composite structure and specific values of loads, shown in Table 5. Firstly, for every type of steel section (IPE, HEA and HEB) and for each composite beam span, design procedure given in EN 1994-1-1 [22] is followed in order to acquire required resistance of cross-section and shear connection. Hereafter, it was tried to find a specific steel section from a range of analysed cross-sections which satisfies recommendations of vibrations for each composite floor class according to JRC55118 [15], and in the same time acquire required resistance of cross-section and shear connection according to EN 1994-1-1 [22]. At last, for specified cross-section total vertical deflection of composite beam $\delta_{total}$ is determined as summation of vertical deflection of steel beam during construction and vertical deflection of the composite steel-concrete beam after the shear connection is achieved. The results of the parametric study are presented in the form of beam span ($L$) vs. beam span/total deflection ($L/\delta_{total}$). To achieve the evenness of the parametric analysis for every composite beam span, every beam is analysed as unpropped during construction. Considering that the serviceability limit state is authoritative criteria for this analysis, the variation of steel grade for structural steel is irrelevant. Therefore, structural steel for all composite beams is made from steel grade S235, as given in Table 5.

Composite floor structures with lower class are more favourable for a wide range of floor occupancies, as given in Table 4. Concrete slab and profiled steel sheeting height of composite slab shown in Table 5 are adopted as minimal values in order to accomplish required design resistance for adopted load value and which offers a safe prediction to the floor vibration vs. deflection.

The main result of the parametric study is the direct relation between vertical deflection of composite beams and achieved floor class, according to floor vibrations classification given in JRC55118 [15]. Therefore, according to the results of this parametric study, verification of floor deflection can lead directly to the classification of floor vibrations.

### 3.2 Results of the parametric study

Results of parametric analysis for composite beam spacing of 3 m of composite structure CS 1 which dimensions are shown in Table 5 and imposed load of 2.0 kN/m$^2$ are shown in Figure 4. For analysed composite beam total vertical deflection is determined for achieved composite floor class due to vibrations, as explained in the previous chapter. Beam span/total deflection ($L/\delta_{total}$) is plotted versus the span of the analysed composite beam (Figure 4).

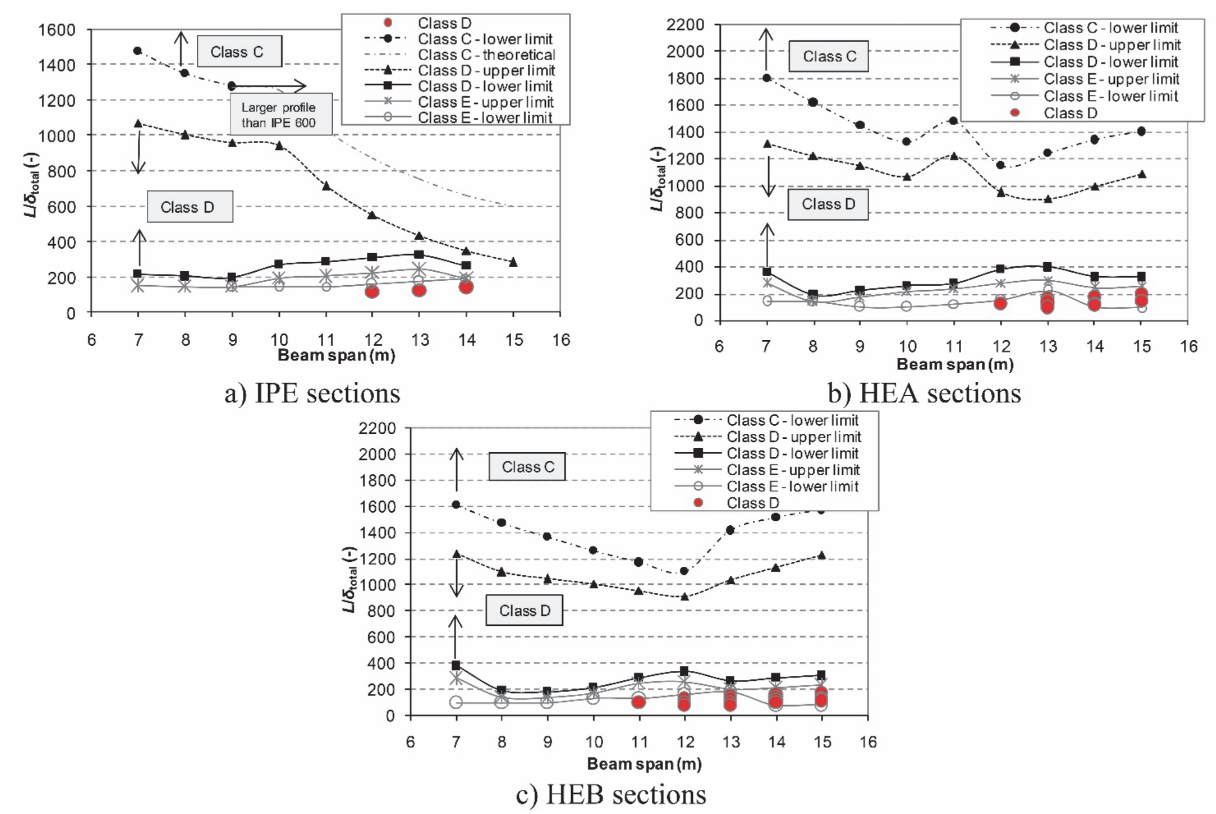



*Figure 4. Deflection of composite beam for beam spacing of 3 m and imposed load of 2 kN/m$^2$ - CS 1*

For composite structure CS 1, class A and B with analysed hot-rolled steel sections could not be accomplished, as shown in Figure 4. The same behaviour is obtained for two other composite structures CS 2 and CS 3. In additional, similar behaviour is achieved for HEA and HEB steel sections of composite beams, while IPE sections show somehow different behaviour. Moreover, for composite beam span higher than 9 m, floor class C could not be accomplished even with the larger IPE section (IPE 600). The theoretical extension of the curve which represents vertical deflection for class C is derived based on the results for class D, as shown in Figure 4a. Difference between vertical deflection for the lower limit of class C and the upper limit of class D is the result of different geometrical properties of two consecutive cross-sections. In addition, with standard IPE, HEA and HEB cross-sections composite floor class E can be accomplished, but with very high values of vertical deflection.

The widest range of cross-sections lead to the composite floor class D, and class C is achieved for beam span/total deflection values higher than 1400 for IPE sections and 1800 and 1600 for HEA and HEB sections, respectively. It can be concluded that for composite structure CS 1 the higher efficiency considering floor vibrations can be achieved for beam span of 12 m, using HEA and HEB steel sections. In addition, using the consecutive cross-sections from lower to the largest, higher floor class can be achieved with a smaller cross-section and for larger cross-section lower floor class, which is presented in form of red dots on the plots in Figure 4. This is the outcome of the composite floor class diagrams presented in Figure 2b which are not given in form of linear relation between modal mass $M_{mod}$ and fundamental natural frequency $f_0$, especially for fundamental natural floor frequencies of 2 Hz and 4 Hz, which present the range of frequency of pedestrian walk.

Comparison of cross-section design resistance utilization level for composite structure CS 1 with imposed load of 2 kN/m$^2$ is given in Figure 5. It is shown that the achievement of class C for three different steel sections can be accomplished with cross-section design resistance utilization level amounting approximately 20 %. The lower limit of composite floor class D which beam span/total deflection ($L/\delta_{total}$) ratio is in the range from L/200 to L/400 (Figure 4) is achieved with a cross-section which utilization level is from 50% to 70% for IPE sections and relatively equally for HEA and HEB sections (40 % to 50 %). The analysis presented in Figure 5 is accomplished for various cross-sections, aiming to achieve different composite floor classes with lowest possible cross-section dimension, but also accomplishing design procedure for the ultimate limit state.

Comparison of beam span ($L$) vs. beam span/total deflection ($L/\delta_{total}$) plots for composite structure CS 1 and different values of imposed loads are given in Figure 6. The higher value of imposed load leads in the achievement of designated floor class with smaller steel section, higher value of vertical deflection and lower beam span/total deflection ($L/\delta_{total}$) ratio. The same trend is noticed for three analysed steel section IPE, HEA and HEB, as shown in Figure 6. The lower limit of floor class D for three analysed steel sections have similar values for four analysed imposed loads values. The same behaviour is noticed for other analysed composite structures CS 2 and CS 3.

The parametric study presented in this paper included a wide range of composite beam spans, with most common composite floor spans. In addition, analysed loads included usual values of additional permanent loads and whole range imposed loads which are defined according to EN 1991-1-1 [18]. Results of three analysed composite structures (Table 5) are compared in order to define unique beam span ($L$) vs. beam span/total deflection ($L/\delta_{total}$) plots for three different types of hot-rolled steel sections (Figure 7). The results presented in Figure 7 offers the safe (conservative) prediction of composite floor class due to vibrations. Values of beam span/total deflection ($L/\delta_{total}$) which are higher than values given with red curve presented in Figure 7 gives a safe (conservative) prediction for class C composite floor, and values which are between black curves (upper and lower limit for class D) gives a safe (conservative) prediction for class D. For values which are between curves which present upper and lower limit for specified class, the design procedure for composite floor classification given in JRC55118 [15] should be performed in order to confirm composite floor class. In addition, it is important to highlight that the values of total vertical deflection $\delta_{total}$ presented on plots in Figure 4, Figure 6 nad Figure 7 are obtained through the summation of vertical deflection through all construction

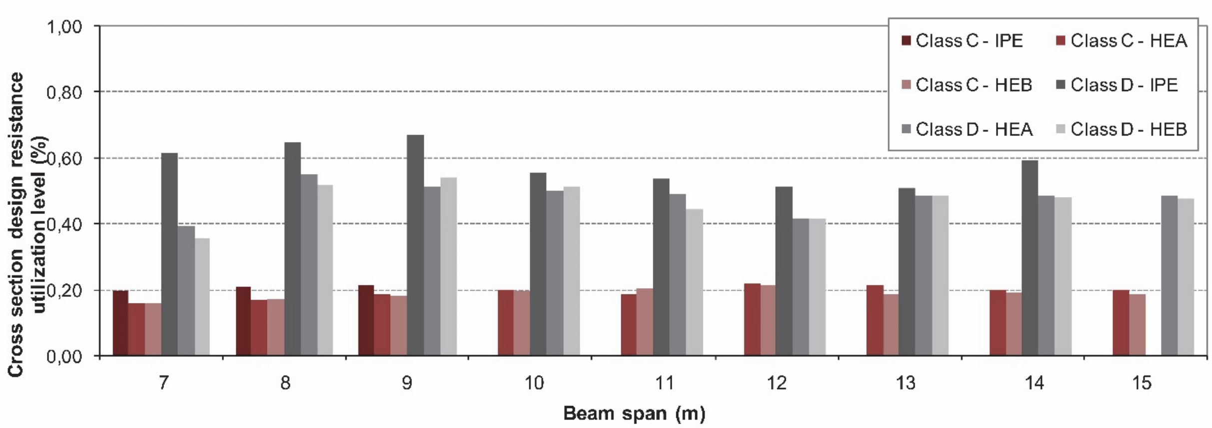



*Figure 5. Design resistance of composite steel-concrete cross section - CS 1*

phases without support within the span of the steel beam during construction or precamber of the steel section. In order to accomplish vertical deflection limitation according to EN 1994-1-1 [22] precamber of steel sections for the value of the deflection during construction can be performed.

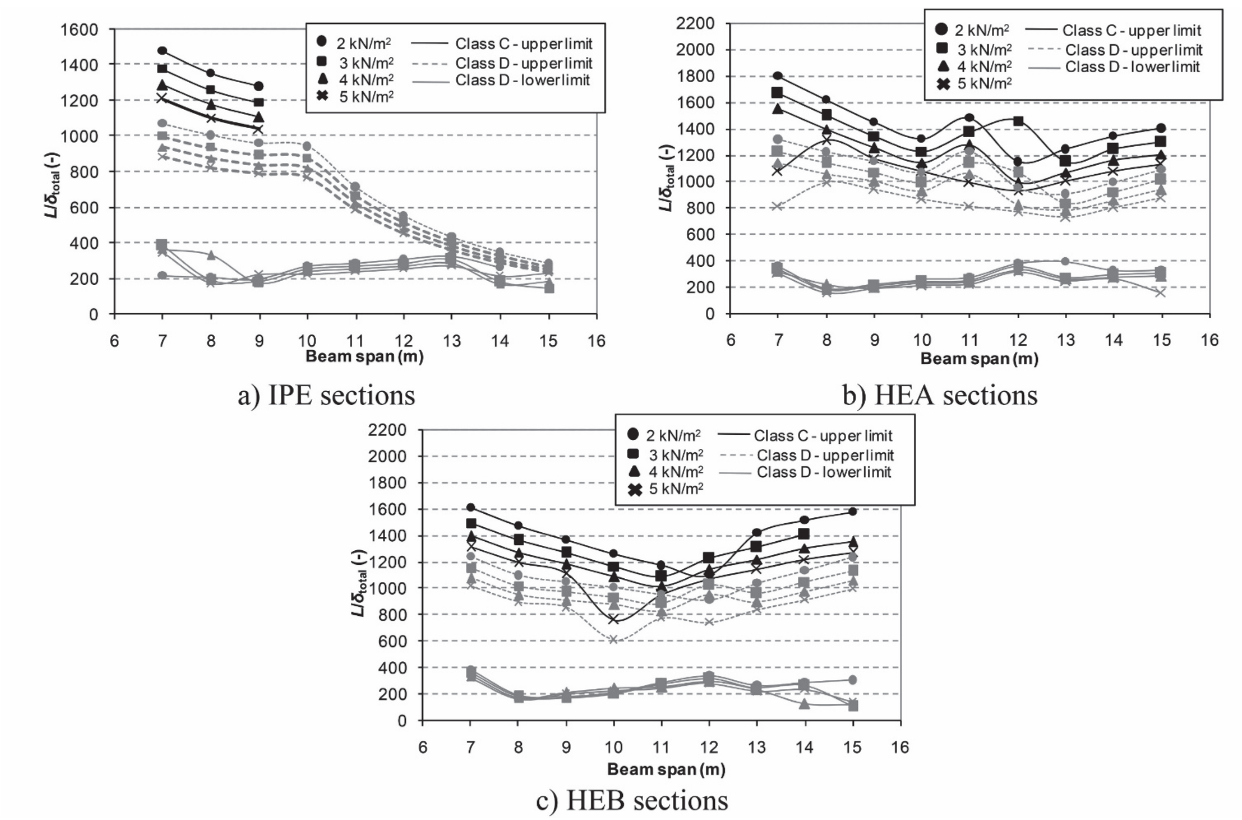
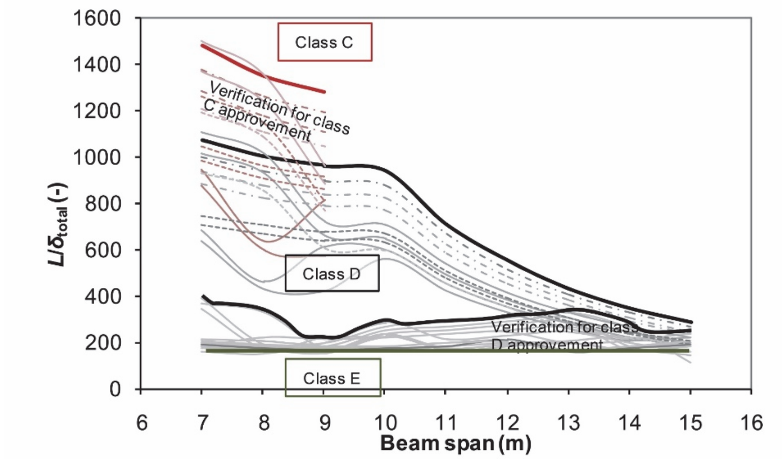
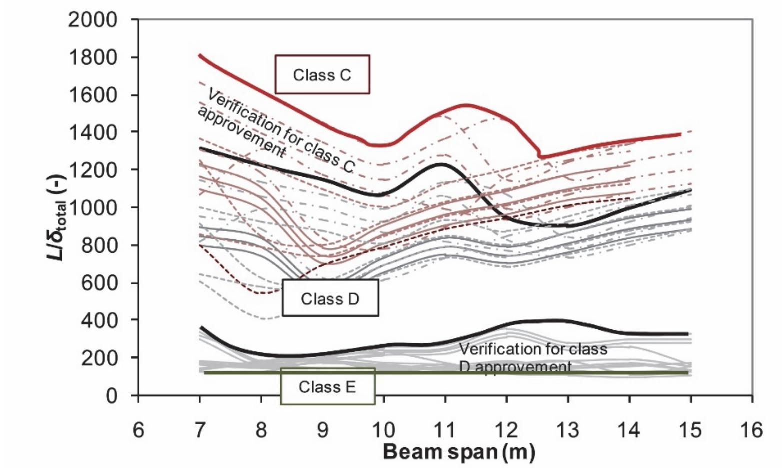


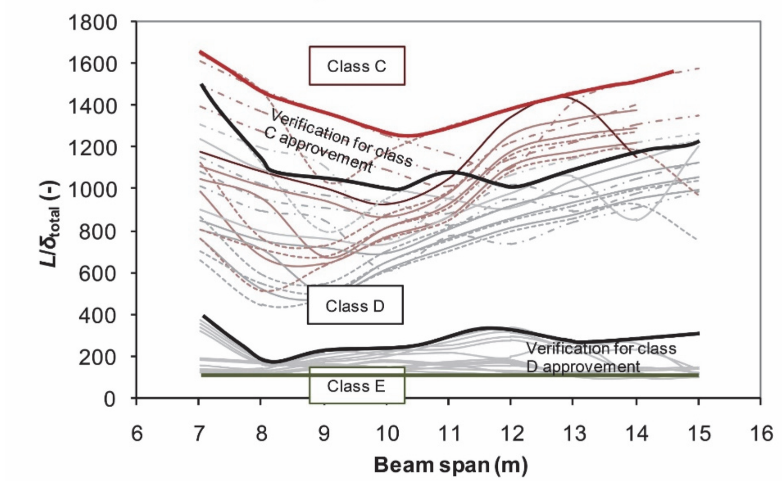

*Figure 6. Comparison of vertical deflections for different values of imposed loads – CS 1*




a) IPE sections




b) HEA sections




c) HEB sections

*Figure 7. Composite floor class vs. beam deflection*

3.3 Discussion of parametric study results

According to the results of the parametric study, the following remarks can be stated:

1) Even the largest steel sections from the range of IPE, HEA and HEB hot-rolled steel sections used in the parametric study presented in this paper cannot lead to the achievement of composite floor class A and B due to floor vibrations according to JRC55118 [15]. Moreover, the lowest floor class F is not accomplished, considering that small structural steel sections would not satisfy cross-section design resistance.

2) IPE steel sections are favourable for beams with larger spans for the achievement of designated composite floor class due to vibrations. HEA and HEB steel sections showed relatively similar behaviour, and this type of steel sections shows the best achievement of designated composite floor class for spans between 10 and 12 m for three analysed composite structures.

3) The widest range of adopted steel sections and composite beam and floor class results in the achievement of composite floor class D. Composite floor class D is not recommended for the usage in critical working areas, hospitals, surgeries, schools and training centres

## 4 Conclusions

Architectural trends towards slender structural design and using modern high-strength construction materials often result in low natural frequencies of the structure. Therefore special attention should be given to serviceability limit states verification, which can often be authoritative criteria for structures design. Subsequent re-design of structures which fail to satisfy vibrations acceptance criteria for the intended use of the structure is very difficult, not economical and often unfeasible. Design recommendations dealing with composite floor vibrations are given through different technical guidelines or recommended procedures which are not mandatory for the structural design. Moreover, Eurocode defines only rough (indicative) recommendations for evaluation of acceptance criteria regarding vibrations of floor structures and fails to provide more precise recommendations for calculation of floor structures exposed to vibrations.

In this paper, the results of numerical analysis and parametric study of composite beams due to vibrations induced by pedestrian loading are presented. The following conclusions are obtained:

1) Vertical root mean square accelerations obtained from numerical analysis using FE software are significantly lower than the same values obtained from simplified design procedures. Lower vertical accelerations lead to lower composite floor class due to vibrations which are favourable for different floor occupancies.

2) Composite floor beams which are designed in order to accomplish recommendations for the ultimate limit state with high level of utilization most often leads to the floor classes due to vibrations which are between class D and E. Safe prediction of composite floor class D leads to the utilization level form 50% to 70% for IPE sections and from 40% to 60% for HEA and HEB hot-rolled steel sections, according to JRC55118 [15]. Composite floor class D can be used for residential buildings, office buildings, meeting rooms, senior citizens residential buildings, hotels, industrial workshops and sports facilities.

3) Lowering the level of utilization of composite cross-section resistance to 20%, leads to the composite floor class C, according to JRC55118 [15]. Composite floor structures of class C are not recommended only for critical working areas and can be used for all other occupancies.

4) Composite floor classes A and B cannot be accomplished with standard hot-rolled steel sections and achievement of high floor classes can be reached only with specifically built-up steel members, according to design recommendations given in JRC55118 [15]. The main difference between these floor classes and composite floor class C is that floors with class C cannot be used in critical working areas where specific working activities are envisaged or installation of equipment with high precision. These types of floor occupancies are very specific and detailed composite floor verification based on the precise numerical analysis of vertical vibrations should be performed.

5) The results of the parametric study presented in this paper can be used for safe (conservative) prediction of composite floor class against vertical floor vibrations, based on the determination of composite beam vertical deflection.

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# Review of research in the function of structural engineering development in Serbia*

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**ABSTRACT**

Research at faculties in Serbia after WWII, even though they were fruit of individual efforts, resulted in significant theoretical contributions. Organized, mostly applied research was conducted within institutes with participation of scholars and researchers of the faculties. Since 1952, the Association of Yugoslav Laboratories (AYL) consolidated the research, thus providing a considerable contribution to the structural engineering in Serbia. This contribution in the field of theory and practice was the basis for the notable achievements that glorified our structural engineering worldwide. Theoretical contributions contained in the doctoral dissertations in the field of Theory of structures and Geotechnics are significant, so they were listed in the paper. Majority of these studies became a part of research project as late as in 1976, and they are briefly presented in the paper. The synthesis of project results from fundamental and technological development research was published in numerous monographs, articles, papers and proceedings of scientific and professional meetings and some of them are commented in this paper. The necessity to introduce technical regulations which have already been adopted in the EU countries EN 1990 to 1999, i.e. the Eurocode, was emphasized. There is a brief discussion of several research directions which are topical nationwide as well as worldwide.

## 1 Introduction

Yugoslav Society for Testing of Materials and Structures (YUSTMS), now Society for Testing of Materials and Structures (STMS) of Serbia was preceded by the Association of Laboratories for Testing Materials and Structures founded on May 10th 1952. Subsequently, the scope of the work of the Association was discussed, and it was adopted that its activities should follow the program of RILEM, and that it should contribute to the development of the standards in the domain of methods of material and structural testing (MST) jointly with the Association for Standardization. It was agreed to establish divisions in each Republic. Publication of the Bulletin, as a precursor of the present day journal Building Materials and Structures (BMS), provided better information about obtained results in the field of material and structures. In the first phase of publication, apart from information, short abstracts of the papers delivered on the annual assembly meetings were published as well. Although in creation of the structures, the most important place belongs to designers, their relation with researchers and manufacturers (prefabricated elements building) and contractors are significant. Materials and structures are often considered jointly, as the research and improvement of materials and their properties is of special interest for the development of structural engineering.

The research described in this paper, was realized in different periods and under different conditions, and span the period from WWII till the present days. However, in the monographs [44] several periods were included. The first refers to the work of the Great school 1903-1905, the second to the operation of the Department at the Technical Faculty of the University of Belgrade with the status of teaching civil engineering over the period 1918-1941. After the WWII, the Technical faculty proposed consolidation of the studies and in1948 the Faculty of Civil Engineering was established (FCE), and its educational reforms until 1978 were described in the monograph. The faculties in other educational centres, i.e. Niš, Priština, Novi Sad and Subotica were formed with a significant effort of scholars and researchers of the FCE Belgrade. Even though several institutes were established after WWII, faculties were also engaged in scientific-

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research work and facilitated cooperation with the economy, mostly through their institutes. The research work at the faculties in Serbia after WWII was the result of enthusiasm and individual efforts with significant theoretical contribution. Organized, mostly applied research was conducted within institutes with participation of scholars and researchers of the faculties.

Association of Yugoslav Laboratories (AYL) since its foundation in 1952 unites the research work of the institutes and directs it towards topical issues in civil engineering, with strong synergy of theory and practice. Such operation, even though it was insufficiently financially supported, considerably contributed the development of structural engineering in Serbia in realization of a number of structures which represent remarkable achievements at the global level [1] and [8]. The theoretical contribution of doctoral dissertations and master thesis in the field of theory of structures and geotechnics was the basis and encouragement to the development of structural engineering in our country. Only since 1976 the work on the doctoral dissertations was connected to the research projects, which were financed from the funds of the Republic and Autonomous regions, or from other sources (economy, chamber). The list of doctoral disserta¬tions is presented in this paper along with the titles from which one may observe the themes considered and their importance for structural engineering. Only some of the research projects in the field of fundamental and technological development research were commented upon and in addition, the important publications resulting from them are listed. In Serbia, a research work on the studies and translation of technical regulations adopted in the EU countries with the designations EN 1990 do 1999, which are often called Eurocode started ten years ago. The need for further systematic work on their application into practice in our country is emphasized.

In the recent years, an increasing number of researchers is focused on publishing research results in international journals and proceedings from international scientific meetings. The synthesis of results of earlier research projects is published, mostly in our country in a number of monographs, articles in journals and proceedings from scientific and professional meetings which is only partially commented in this paper. In brief, several topical directions of future research in our country and worldwide is mentioned. In this sense, a wider list of references is made indicating the relevance to current interests of contemporary research themes in Serbia.

## 2 Defended doctoral dissertations at faculties of civil engineering in Serbia

### 2.1 Doctoral dissertations defended at the Faculty of Civil Engineering in Belgrade

Dragoš Radenković: *Bending of curved members in plane* (1953); Milan Đurić: *Theory of long prismatic polyhedral shell* (1953); Vladimir Bogunović: *On bending of rectangular plate with one degree of freedom* (1953); Nikola Hajdin: *One procedure for numerical solving ultimate (boundary) tasks and its application on some problems of Theory of elasticity* (1956); Vlatko Brčić: *Toward the solution of flat problem of the Elasticity Theory* (1956); Aleksandar Vesić: *Fundamental problems of theory and calculation of a system of piles* (1956); Dušan Krsmanović: *Impact of stiffness, continuity and discontinuity on calculation of structures supported on the soil* (1957); Milorad Ivković: *Behaviour of concrete in the area of limit equilibrium* (1962); Živojin Hiba: *Towards the theory of steel anchored suspended bridges with the beam for stiffening the incomplete flexibility* (1963); Branko Zarić: *Buckling of steel members in the plastic area* (1963); Vlade Vračarić: *Cooperation of deck and main beams of steel truss railway bridges* (1965); Dimitrije Dimitrijević: *Behaviour of RC and composite members with participation of concrete creep at dynamic load* (1973); Jakov Lazić: *Application of linear visco-elasticity in the structural theory* (1973); Miodrag Sekulović: *Thin-walled member curved in space* (1973); Mihajlo Muravljov: *Behaviour of thin-walled open-profile members of pre-stressed concrete at limited torsion with the concrete flow effects* (1975); Ratko Stojanović: *Resistance of paraseismical structures on the action of explosive shock* (1975); Vera Lazić: *Dynamic stability of curved members of visco-elastic material* (1975); Milutin Marjanov: *Solution of composite problems of thermal-elasticity in a confined environment* (1977); Milan Gojković: *Stone bridges from the 14th to the 18th century in Yugoslavian boundaries* (1977); Milan Lazić: *Parameters of general optimality when using light-aggregate concrete in panel construction of housing buildings* (1977); Boško Petrović: *Behaviour of skeletal buildings of pre-stressed concrete under the action of seismic forces* (1977); Radoje Vukotić: *Limit states of members of reinforced and pre-stressed concrete loaded by torsion and bending* (1977); Vojislav Mihailović: *Generalized procedure of design of composite and pre-stressed structures* (1978); Dragoljub Nikolić: *Some problems of non-linear analysis of curved members* (1978); Predrag Jovanović: *Towards a structural matrix analysis* (1978); Mirko Aćić: *Towards solving the issue of limit states of reinforced concrete bearing walls* (1978); Stevan Stevanović: *Towards solution of in-plane problem of the theory of elasticity for some semi-infinite areas bounded by polygonal contours* (1978); Milivoje Stanković: *Towards a design of thin-walled members with deformable cross-section* (1978); Živorad Radosavljević: *Analysis of rationality of ultimate limit state of concrete* (1978); Života Perišić*: A contribution to determination of creep and shrinking effects in cracked reinforced concrete cross sections with cracks* (1979); Aleksandar Pakvor: *Towards a study of thermal stresses and strain of concrete blocks* (1979); Šerif Dunica: *Towards a plastic analysis of spatial linear systems, composed of truss, full and thin-walled elements* (1979); Živojin Praščević: *Non-linear theory of reinforced concrete member* (1979); Miloš Manojlović: *Towards a theory of dynamic behaviour of soil* (1979); Branislav Kolunžija*: Towards a second order theory of spatial linear systems composed of truss, full and thin-walled elements* (1979); Dušan Milovanović: *Latest findings in the theory of arch dams* (1980); Čedomir Vujičić: *Towards optimizing design of reinforced concrete walls built directly on soil* (1980); Savo Vukelić: *Analysis of mechanical states of hardened concrete – thermo-dynamical approach* (1981); Milorad Ristić: *Towards an analysis of elastic, pre-stressed networks* (1981); Slavko Zdravković: *Mathematical* *modelling of bridge road decks structures to dynamic and seismic action* (1981); Branislav Ćorić: *Theoretical and experimental analysis of local and lateral buckling of steel I beam of a deformable cross section* (1982); Dragoljub Grbić: *Oscillations of elastic members at ultimate displacements* (1982); Radomir Folić: *Towards a study of T beams – analysis of active slab width and ultimate states of reinforced concrete pre-stressed concrete elements* (1983); Srđan Venečanin*: Impact of thermal incompatibility of concrete components on its strength* (1983); Jovanka Zurovac: *Towards an analysis of elastoplastic behaviour of reinforced concrete beam* (1983); Petar Petrović: *Numerical solution of Lame's equations of the elasticity theory using the integral equation method* (1985); Dimitrije Rajić: *Towards a non-linear theory of thin elastic shells and its application* (1985); Kisin Srđan (then from Sarajevo): *Towards a theoretical experimental analysis of lateral buckling of mono-symmetrical beams of deformable cross section* (1985); Aleksandar Babović: *Ultimate limit state of eccentrically compressed RC columns in steel tubes* (1985); Dejan Bajić: *Towards non-linear analysis of RC linear elements* (1985); Stanko Brčić: *Dynamic behaviour of structures in fluid environment* (1987); Cvijetin Kanjerić: *Analysis of flat frame beams stressed beyond the proportionality limit* (1987); Živorad Bojović: *Elastic damped systems exposed to the load which depends on their configurations under small strain and large displacements* (1988); Miloš Lazović: *Towards a non-linear analysis of axially loaded pile* (1988); Đorđe Vuksanović: *Non-linear analysis of reinforced concrete slabs by the finite element method* (1988); Rastislav Đorđević: *Towards an analysis of long-stroke tooling machines foundation behaviour in service conditions* (1989); Gligor Radenković: *General non-linear analysis of shells based on triangular and general quadrangular finite element* (1989); Branislav Pujević: *Towards a non-linear analysis of thin-walled reinforced concrete structures* (1989); Dragan Buđevac: *Towards a design and structural formation of cold-rolled profiles of an open cross-section* (1990); Mihajlo Đurđević: *Behaviour of concrete composite prefabricate elements and connections in the area of failure* (1990); Aleksandar Prokić: *Thin-walled beams of open-closed cross-section* (1990); Ljubomir Savić: *Towards a mathematical research of some statistical problems of non-linear behaviour of structures* (1990); Gajin Slobodan: *Non-linear dynamic analysis of foundations of electro-mechanical transmissions and their vibro-insulation* (1992); Biljana Deretić-Stojanović: *Design of composite structures using strain method* (1992); Mira Petronijević: *Analysis of dynamic interaction of soil and structure applying finite element method* (1993); Rastislav Mandić: *Modelling interaction of reinforcement and concrete in reinforced concrete structures applying the finite element method* (1994); Milan V. Matović: *Towards an analysis of stress and displacement of thin-walled composite beams* (1996); Želimir J. Kovačević: *Concrete bridges maintenance management systems* (1997); Dragan Č. Lukić: *Towards a method of defining the stress state around the cavity in the form of rotating ellipsoid applying elliptical coordinates* (1998); Miroslav T. Bešević: *Towards an analysis of centrically loaded steel members of complex cross-sections of cold-rolled profiles* (1999); Petar B. Santrač: *Analysis of strip foundation behaviour on sand* (1999); Zoran M. Mišković: *Application of stress fields based on the theory of plasticity for determination of ultimate limit state of reinforced concrete bearing walls* (2000); Ratko M. Salatić: *Analysis and control of behaviour of steel frames at earthquake action* (2001); Snežana B. Marinković: *Ultimate limit state at punching shear of prefabricated pre-stressed slabs in the area of fringing columns* (2002); Dušan I. Kovačević: *Numerical modelling behaviour of reinforced concrete frames loaded by seismic forces* (2002); Milorad T. Komnenović: *Analysis of stress states of curved beams of laminated glued timber loaded by bending* (2002); Zlatko A. Marković: *Towards an analysis of bearing capacity of mechanical connectors for thin-walled steel elements* (2002); Boško D. Stevanović: *Behaviour of composite beams timber-concrete constructed with mechanical connectors at service and limit load* (2003); Vlastimir S. Radonjanin: *Parametric analysis of characteristics of repair mortar from the aspect of their application during rehabilitation of reinforced concrete structure* (2003); Nenad G. Marković: *Buckling of tin beams under the action of the local load* (2003); Mirjana Ž. Vukućević: *Application of elasto-plastic models for soil in design of flexible support structures* (2007); Ljudmila /Timofejev/ Kudrjavceva: *Thermoviscoelasticity and damage of composites on polymer basis* (2007); Vladan M. Kuzmanović: *Towards a thermal design of gravity dams of rolled concrete* (2007); Špiro L. Gopčević: *Non-linear analysis of structures with cables* (2007); Snežana Mašović: *Redistribution of impacts in subsequently extended composite reinforced concrete beams in time* (2008); Ruža Okrajnov-Bajić: *High early strength SCC in elements with prominent main tensile stresses* (2009); Ljiljana Žugić-Zornija: *Non-linear analysis of cable-stayed bridges* (2009); Dimitrije Zakić: *Research of the parameters of ductility and impact resistance of fine grain concretes micro-reinforced by synthetic fibres* (2010); Marina Ćetković: *Non-linear behaviour of laminate composite slabs* (2011). At the Faculty of Mathematical and Natural Sciences, Slavko Ranković defended the dissertation in 1973, and at E.P.F. in Lausanne Dušan Najdanović (1987).

There are several dissertations defended by the candidate from other Republics, mostly from Macedonia with very topical themes at the time dealing with earthquake engineering, and several from Montenegro, dealing with experimental and theoretical research of structures. From Slovenia, there is a dissertation related to the interaction and rheological material issues - Houška Mladen: *Interaction of the structure and foundations regarding the static and rheological characteristics of material* (1980); From Macedonia: Apostol Poceski*: Impact type earthquakes and paraseismical construction* (1968); Jakim Petrovski: *Modelling soil and structure parameters to the dynamical reaction of dug-in foundations* (1974); Dimitar Jurukovski: *Formulation of the mathematical model of two-storey high steel frame applying parametric identification of the system* (1981); Boris Simeonov: *Linear and nonlinear behaviour of reinforced-concrete diaphragms of multi-storey structures* (1982); Predrag Gavrilović: *Shear strength of reinforced concrete structures in nonlinear area for cyclic and dynamic loads* (1982); Ištvan Kladek: *Prilog kon primenata na varijacionite metodi za rešavanje na tenki ljušpi (Towards an application of variation methods for designing thin shells)* (1983); Andrej Spasov: *Model of short duration earthquake* (1984); Goce Popovski: *Experimental and theoretical* *research of connections of prefabricated and subsequently placed concrete* (1988); From Montenegro Duško V. Lučić: *Towards stability analysis of thin-walled beams* (1999); Pero A. Vujović*: Influence of weathering strain on the ultimate limit states of reinforced concrete slabs stressed in their plane* (2000); Radomir M. Zejak: *Towards an analysis of obliquely bended slender reinforced concrete elements* (2003); Olga Mijušković: *Stability analysis of rectangular slabs using accurate stress function* (2008).

### 2.2 Doctoral dissertations defended at FCE (Faculties of Civil Engineering) in Niš, Priština, Novi Sad and Subotica

During the 1970s, there were several leading visiting researchers at FCE in Niš among whom the famous Prof. Marcel Save delivered lectures at Seminars dealing with the past and present topical field of studies of the Theory of plasticity. This inspired the scholars and researchers to fully engage in this field of studies, so a number of dissertations was written dealing with the same subject and its application for optimal structural design. The following dissertations were defended: Tomislav Igić: *Towards an optimum design of structures* (1980); Milić Miličević: *One procedure of limit analysis of transversely loaded polygonal plates with the special focus on trapezoidal plates* (1980); Dobrivoje Stanković: *Finite elements method* (1980); Tomislav Radojičić*: Main stresses and ultimate bearing capacity of elements* (1980); Sreten Stevanović: *Ultimate bearing capacity of linear beams*; Dragutin Rodić: *Towards a solution of the problem of medium columns of bridges*; Popović Branko: *Problems of ultimate failure state of linear systems of classical RC structures* (1982); Grozdana Radivojević: *Effects of variation of stiffness on the elastic stability of linear systems* (1982); Dragoljub Drenić: *Analysis of crack propagation under the action of impact load in the high strength steel* (1982); Novak Spasojević: *Forced damped vibrations of beam systems in plane with a special focus on bridge structures* (1983); Milisav Damjanović: *Towards a solution of architectonic-structural problems of high-rise buildings in the system of spatial frame structures with wall bars* (1983); Dragan Veličković: *Determination of ultimate bearing capacity of arbitrary cross section of thin-walled beam with a deformable contour* (1985); Miodrag Đinđić*: Stability analysis of tunnel structures of horse-shoe cross-section in elasto-plastic environment, depending on construction technology* (1985); Hristo Kapsarov: *Towards aseisimic design of tower-type high RC facilities* (1985); Dušan Petković: *Concrete-concrete composite* (1987); Dragoslav Stojić: *Lateral stability of glued laminated timber beams loaded to bending and torsion* (1987); Verka Prolović: *Foundations of smith hammers as sources of vibration and their influence on adjacent structures* (1992); Ljubomir Vlajić: *Behaviour of connections with friction grip bolts at service and ultimate load* (1993); Vladimir Radojičić: *Bending of beams of high early strength concrete with lateral forces* (2000); Marina Mijalković: *Analysis of stress and strain state of spatial linear girders according to second order theory* (2001); Dragan Kostić: *Towards the solution of the stability problem of double catenary systems* (2007); Zoran Bonić: *Towards a theory of calculation of failure by punching shear of foundation footings supported by deformable subsoil* (2011); Slobodan Ranković: *Experimental-theoretical analysis of ultimate limit states of RC linear beams strengthened by composition with NSM fiber composites* (2011); Predrag Blagojević: *Experimental-theoretical analysis of ultimate limit states of micro-reinforced concrete beams* (2012).

The following dissertations were defended at the Faculty of Civil Engineering in Priština: Vukomir Savić: *Mixed Finite elements method for cylindrical shells* (1986); Petar Čolić: *Ultimate limit states of composite prefabricated concrete structures* (1987); Aleksandar Ristovski: *Behaviour of pre-stressed structures in time, under long-term loads* (2001); Mirsad Tarić: *Towards the design of composite structures steel beam – concrete* (2004).

The following dissertations related to structural engineering were defended at the Faculty of Technical Sciences (FTS) in Novi Sad: Svetlana Žorić: *Experimental and analytical research of RC walls with opening under seismic load* (1990); Milan Letić: *Structure of the system for automatic designing of industrialized prefabricated housing buildings* (1991); Mitar Đogo: *Towards a theory of foundation design of finite stiffness in multi-layered system* (1996); Ratko Maretić: *Stability and oscillations of a rotating circular slab* (1997); Slobodan Krnjetin: *Towards a determination of necessary fire resistance of concrete buildings* (1999); Đorđe Lađinović: *Multi-criterion analysis of seismic resistance of structures of reinforced concrete* (2002); Jasmina Dražić: *Analysis of interdependence of functional and structural characteristics of buildings in aseismic designing* (2005); Emil Popović: *Development of the model of maintenance of locks with segmental gates at the example of the hydro-system Danube -Tisa- Danube* (2007); Vladimir Nikolić: *Exploration of the newly proposed pile with widened stem* (2007); Zoran Brujić: *Analysis of ultimate bearing capacity of RC columns bended in two axes* (2008); Tatjana Kočetov-Mišulić: *Behaviour of forged connections of bearing wooden wall panels* (2008); Todor Vacev: *Optimum design of a node of the spatial steel grid applying non-linear analysis* (2009).

The following dissertations in the field of engineering structures were defended at The Faculty of Civil Engineering in Subotica: Danijel Kukaras: *Experimental-theoretical analysis and calculus modelling of behaviour of prefabricated beams connected with friction grip bolts* (2008); Ilija Miličić: *Theoretical-experimental analysis of redistribution of the load when determining serviceability of bridge structures* (2008); Danica Goleš: *Rheologoical-dynamic analysis of RC polyhedral shells* (2012).

## 3 Bulletin, journal, congresses and conventions of YUSTMS/STMS

### 3.1 Bulletin and journal and research in YUSTMS and Institutes

Since 1952 when the Association of Yugoslav Laboratories (AYL) was founded until 1966, assembly meetings and conventions were held, where articles and latest information were presented. They were related to the activities of RILEM-a, research programs of the Institute, and in 1957 it was decided to publish the Bulletin, which is a precursor of MS (Materials and Structure). In the later period, the publication of professional and scientific articles commenced. The works of the Institute researchers were prevailing over those from the Faculty. Until 1960, there was only the Faculty of Civil Engineering (FCE) of Belgrade. FCE in Niš was founded in 1960. In Priština, in the framework of the Technical Faculty, the Civil Engineering curriculum has been taught since 1967, and in Novi Sad since 1971, at the Faculty of Mechanical Engineering, and since 1974 as a part of the Faculty of Technical Sciences. On the same year, the FCE in Subotica was established, and six years ago FCE was founded at the State University in Novi Pazar. All the mentioned Faculties were established with engagement of the scholars from FCE in Belgrade.

At the beginning of its operation, AYL organized congresses with presentation of papers and discussions simultaneously with assembly meetings. At the congress on 12th June 1958 the main presentation was: *Materials and structures in housing construction* (Milutin Maksimović). The need for full prefabrication and assembly of large standard building elements, or application of semi-prefabricated construction was emphasized in this presentation. This was meant to save timber. Prefabrication of floors and ceiling structures was recommended and modular standard measures and usage of light concrete was prescribed. It was the initial impulse for the development of prefabricated systems of building construction. On the occasion of 12th Congress of RILEM held in July 1958, Beograd-Zagreb-Ljubljana, a jubilee issue of the Bulletin 3/1959 was published. The paper of Branko Žeželj: *About the new possibilities offered by the pre-stressed concrete applying prefabrication in skeletal structures* was published in this Bulletin. This paper was the basis for the development of pre-fabricates system IMS–Žeželj. In the Bulletin 3/59 Hubert Rüsch published a brief abstract of the paper: *A newer theory of bending of RC structures on the basis of the testing in Munich – influence of load duration*. This paper influenced the orientation of researchers in this field of studies in our country. More details on this meeting can be found in [37].

The Bulletin published the presentations of significant structures. Thus, in the Bulletin No. 1/1958 new road bridge in Belgrade (Milan Radojković) was presented. Apart from that, the results of testing of wires for pre-stressed concrete were presented and tests of steel by torsion fatigue. The model of the Hall 1 of the Belgrade Fair (B. Petrović) was presented. By testing the influence of age on the concretes with aluminate cement (Vidan Matić) it was determined that except for the increase of strength till 28 days of age and stagnation until 3 months, there was a decrease of strength of 40% after 20 years. For this reason, it was proposed to add anhydrides to aluminium cement so as to prevent the decrease of strength at high temperatures. In addition, the methodology of testing of hydraulic structures (B. Kujunždić) and adhesive for timber structures was presented as well. The review of the papers of the members of the Association in 1957 was given, in which the members of IMS stood out. For the purpose of rational application of materials in structures, resistance of concrete to corrosion and finding protective methods was investigated. Testing structures on the models (Boško Petrović and Dobrosav Jevtić) and testing structures until failure when using domestic wires for pre-stressed concrete were presented. Construction of structures of laminated timber and their application in civil engineering were studied. The structural testing with dynamic analysis of mobile load for road and railway bridges was presented. Technical conditions (specifications) for assembly of steel structures were investigated (SS-ČK).

Along with the 9th annual assembly, the Association convention was held, with two topics: Structures and materials in housing construction and Problems of bearing steel structure. The influence of RILEM and its Congresses and Meetings (colloquia) was present in the choice of topics of the Association, so the following topics were considered: international standards, concrete and influence of passage of time and physical and chemical causes to deformation, cement, mortar, technical timber, fungi infested timber, metals, masonry columns etc. The laboratory for structural testing at FCE in Belgrade became a member of the Association, and the spatial action of truss structures was studied with the presentation of tests of concrete halls and the new bridge on the Sava river, with test of welding capacity, fatigue and plastic properties of steel (designations Č52 and Č37).

An experimental multi-storey building was tested in IMS. Light cellular concrete was tested and considered (IMS), and coffered slabs made of pre-stressed concrete with hollow masonry blocks were tested as well. The issue of industrialization is related to the physics of buildings and flexibility from the aspect of architectonic functional design. A new type of skeletal structure for high-rise housing buildings form which the IMS-Žeželj system developed was presented. In IMS floor ceilings and roof rafters made of pre-stressed concrete were investigated. Relations with architectonic requirements were established (standardization of spans between the bearing walls and openings in them, floor height and other). The activities of RILEM and their recommendations (effects of age on concrete, influence of constant load and fatigue) were published in the Bulletin. Bearing steel structures were more thoroughly researched in Slovenia.

In the Bulletin No. 3/60 a review of papers– tasks in IMS was given: nature of the task, description of work, phases of production, results and publication, development and improvement of the equipment for pre-stressing, testing stress losses (B. Petrović), standardization of structures in housing construction, standardization of formwork for concreting works, prototypes of high voltage pre-stressed concrete poles, buckling of pre-stressed concrete members.

At the 10th assembly meeting in Zagreb, in 1960, the need to link the research work and "production capacities" was emphasized. In addition, linking design and building with research work was pointed out as well. The paper of B. Žeželj about the problems of scientific work in civil engineering was published in Bulletin No. 1/60 where the role of AYL was emphasized. In addition, in the other issues, the information about the activities of the Institute was provided. The expert committees were established, among which the Committee for industrialization of building (Head - B. Žeželj) and subcommittee for the research of concrete corrosion. Prof.

M. Radojković presented the paper about bridge testing. In Bulletin No. 4/61 works of the Institute "Jaroslav Černi" for hydraulic structures, for the dams with model static tests were presented along with the work on technical instructions for calculus of stress state in the silo bays (cells) and study of arch dams (buckling of arcs) were published. In addition, the work of the Committee for concrete in IMS and for soil mechanics and foundation engineering with conclusions was presented. In the issue No. 4/61 Vidan Matić published the paper on application and protection of steel cables in civil engineering (types and cables) and J. Hahamović on the fire protection.

Scholars in the Institute "Jaroslav Černi" worked on auscultation of several dams, testing pile bearing capacity and pre-stressing of linings of hydraulic engineering tunnels. The application of photo-elastic methods for testing stress states and other methods adapted to the specific properties of hydraulic structures (dams) started, not only in Serbia but in other republics as well. At FCE, steel was tested on impact, strength of welded seams for the bridges across the Danube in Belgrade. In addition, the stress concentration of gusset pieces and the effects of apertures on the mentioned bridge were tested, as well as the carrying capacity of the cranes. Stress-optical analysis was applied on the spatial models.

Similarly as in RILEM, on 3rd December 1959, the Committee for concrete was founded, whose chair was professor Dobrosav Jevtić, in order to unite the research work of concrete technology and concrete structures which the collective and individual members of the Association were conducting, and to organize conventions regarding certain issues of Concrete structures which were important for further development and improvement of concrete and concrete structures.

In issue No. 1/62 Borislava Zakić's paper on the application of the theory of failure in timber structures was published. The activities of the Institute "Jaroslav Černi" and subcommittee for concrete corrosion were described. In the issue No. 2/62 V. Joksić wrote about concrete corrosion, and L. Jovanović wrote about the devices for loading static models in the Institute "Jaroslav Černi". In the issue No. 3/62 there is a presentation of the bridge across the Danube in Novi Sad (B. Žeželj) and the prefabricated pre-stressed concrete system (PC). V. Brčić wrote about the 6th Congress for theoretical and applied mechanics in Split. In the issue No. 4/62 B. Kujundžić wrote about the state of affairs in the field of rock mechanics and underground works, and I. Karpinski from IMS wrote about research aimed at increasing concrete resistance to corrosion. In the issue No. 1/63 grouting instructions, arch dam design instructions and photo-elastic tests instructions were published and the text about brittle coatings.

Along with the 11th assembly meeting (Belgrade, 1963) the convention of the topical issues in civil engineering was held. The submitted papers considered the topical issues of materials and structures, but also, soil mechanics and foundation engineering (D. Krsmanović). In 1963 the Bulletin was renamed into Materials and structures (MS) after the RILEM journal. Very intensive activities in AYL were stirred by the earthquake in Skopje on 26th of July 1963. In Bulletin No. 2/63 Ž. Hiba wrote about insufficiently strong structures for seismic actions. In the issue No. 4/63, D. Jevtić wrote about some problems regarding the earthquake in Skopje with the program of production of technical documents, recommendations and regulations for construction in seismic areas, and authors from Ljubljana wrote about the theory of plasticity. The considerable experience of the engaged researchers of the Institute while recording the damaged buildings was used for making the first Temporary technical regulations for construction in seismic areas. A special issue was published regarding the earthquake in Skopje. In the journal MS No. 5/63 B. Zakić's paper was published - *Design, production and testing of bearing elements of solid timber and various panels of timber, and testing of wrought and glued support structures, and about durability of concrete structures made with aluminized cement.*

The work of D. Jevtić in the European Committee for Concrete (ECC) and B. Žeželj and B. Petrović in the International organization for pre-stressing FIP was very important since it initiated our active participation in the international cooperation. D. Jevtić wrote about ECC and the effects of the earthquake in the issue No. 1/65. In No. 3/65 Natalija Naerlović-Veljković published: *Towards the study of thermal deformation of cylinders of non-elastic material*, in No. 6/65: *Towards the calculation of thermal stresses in a hollow sphere*. In No. 4/65 V. Brčić published: *Application of photo-elastic coatings when testing structures and their models,* and in No. 2/66: *Towards photoviscoelastic testing of structures*. Z. Pavlović wrote the review of the technical regulations (TR) for support (bearing) steel structures. In the issue No. 5/66 V Joksić from the Institute "Jaroslav Černi" wrote: *Grouting instruction*, D. Milovanović wrote about testing of counterforts of multiple arch dams, O. Marković wrote on standardization of bridges on irrigation and drainage canals, K. Ivanović wrote about the effects of earthquakes on tall dams. Z. Pavlović and K. Ivanović wrote about the study of rational designing and construction of locks and gates. V. Brčić et al. wrote about stresses and abutments of dams, and V. Brčić and A. Pakvor wrote about photoelastic testing of the nuclear reactor casing and model tests of the stress in the system dam-rock (interaction). The themes of the Bulletin No. 4/66 were: Construction and technical regulations from the aspect of contemporary needs and adaptation of foreign regulations; about control and safety of tall dams. The emphasis was on the attitude that improvement of the regulations was a prerequisite for the improvement of the quality of BMS (building materials and structures).

The research of the calculation methods of arch dams was carried out with static model tests, on spatial models in the elastic area, and until failure. The tests of the dynamic calculation of dams *in situ* were done on the dams on Zlatibor and Modrac (B and H). Therefore, the mechanics of rocks and geotechnics was researched, by P. Anagnosti and R. Stojadinović with associates. Ž. Radosavljević with B. Kujundžić and associates in the Institute "Jaroslav Černi" developed the design methods of pressurized hydraulic structure tunnels, and published two monographs: *Grouting of hydraulic engineering tunnels and shafts under pressure* and *Pre-stressed linings of hydraulic engineering tunnels under pressure.*

In the issue No. 5/66 the general report of Milan Krstić: *New and improved structures which were prepared for the Symposium and the 12th Congress* (Sarajevo 1966) along with the papers of the members of the Association as well as the reports were published. It is underlined that "it is necessary to construct sufficiently safe structures with the minimum consumption of material and labour. It is a basic task of structural engineers and constructors. The science should not provide theoretical elaborations of already realized practical achievements, but it should take the lead". The papers were organized into groups and presented. The first group of papers was theoretical, the second was tests of constructed buildings, the third was application of new materials in structures, and the fourth was presentation of finished buildings. R. Stojadinović wrote about the potentials of creating new engineering structures on the deposits of waste rock dumps in the industrial zone of Trepča in Zvečan.

In those circumstances, there was a tendency to use nationally conceived devices for structural testing. Thus, a domestic device for production of strain gauge with wide application in structural testing was presented in the issue No. 1/67. The cooperation of scholars at the FCE in Belgrade and Institute "Jaroslav Černi" resulted in several papers and monographs. In the issue No. 2/67 the following paper was published: *Towards the study of underground pressures* by Ž. Radosavljević, Čakarević and B. Čolić, which is important for the tunnels. In the issue No. 4/67 the paper dealing with mechanics of continuous media: *Plastic flow of COSSERAT materials* by S. Đurić was published. The decree of work on technical regulations in the field of civil engineering was issued: for pre-stressed concrete (PC); and for concrete and reinforced concrete (CRC); for the walls; for composite structures steel-concrete; for assembly of steel structures and their protection from corrosion. In the issue No. 2/68 the paper: *Towards the theory of buckling and bending of RC members* by Đorđe Lazarević was published.

Milorad Ivković wrote a paper: *Concrete behaviour in the field of plastic deformations as a part of hydraulic engineering structures*. He provided the initial impulse in this area with his research and paved the way for many young researchers to deal with concrete rheology. Multiple dams were auscultated, bearing capacity of the piles and pre-stressing of hydraulic engineering tunnels were tested. Application of photo-elastic methods in testing the stress states began, as well as other methods – adapting to the specifics of Hydraulic structures, i.e. dams, not only in Serbia but in the other republics as well.

A wider consideration of the research of FCE is given in the separate section. Here is given a review of those already published in the journal M&S. Academician Đ. Lazarević pointed out that research work is inseparable from practice, construction sites, factories and control. This work technique and basis for engineering creativity require knowledge of processing details taking place in the material used for construction, which are particularly interesting for structural engineers from the economic and environmental point of view.

The engagement of the scholars of FCE is particularly important, especially M. Ivković (instructions for calculation of cracks, deformations and rigidity of RC and pre-stressed structures) and D. Jevtić (IMS) at preparation of the Manual for implementation of Code for RC 1972 SJL, i.e. YUSTMS. M. Ivković proposed the calculation of RC member to long lasting load. Thus, he proposed the connection of the stress-strain tensor with introduction of time, that is, age of concrete. In addition, the works of J. Lazić with visco-elastic models, and M. Sekulović with thin-walled members and implementation of FEM are also important. The design of building structures under the action of earthquakes (Dimitrije Dimitrijević), and structure-soil interaction (Miloš Manojlović) are significant as well.

An extensive list of papers published in Bulletin/journal until 2010 is given in reference [10] and they are available in the office of STMS Serbia. The journal was not published over the period from 1984-1988.

### 3.2 Congresses and meetings

Similarly to Bulletin/Journal and apart from the papers which were published in the proceedings of the conferences, the general reports prevalently dealing with the field of material testing were published as well. Only the papers in the function of the development of our structural design were listed in this paper along with undoubtedly significant achievements published in [1] and [8]. The names of the authors were given after the titles of papers or groups of papers. The full list of the papers published in Bulletin/ Journal, which was prepared by Vladimir Denić, is published in the Journal No. 4/2010, pp. 57-116. From the list of the papers, it can be observed that at the beginning, the authors from the Institutes IMS, "Jaroslav Černi" and the others were dominant, while the authors from the Faculties prevailed from the beginning of the 1990s. Having in mind that the society of structural engineers presents the achievements in the area of engineering structures and bridges, the topics concerned with the Theory of structures and their testing during construction and under test loads for verification are dominant in this paper. Exceptionally, there are presentations of the bridges across the Neretva river (D. Ćertić) and the bay of Šibenik (Ilija Stojadinović) which were globally recognized achievements at the time. During the past 10 years, there were obligatory themes regarding application of the set of documents EN 1990 to 1999, i.e. Eurocode for structures. These topics were considered at the conferences of the Society of the structural engineers, and in 1995 and 1997 along with FCE in Belgrade, two large conventions dealing with Eurocode were organized. Papers dealing with concrete structures, metal and timber structures dominated at conventions and Congresses of YUSTMS. Significantly less paper considered masonry structures (MS). Therefore, STMS organized several Meetings.

The first was *Addition of floors on housing and public buildings* (2000) with several sections: socio-economic aspects, architectonic-town planning aspects, seismic resistance, structural aspects, geotechnical aspects, etc. Convention *Masonry structures in contemporary civil engineering practice* along with other topics was dealing with structural and aseismic aspects (2001). Scientific-professional meetings *European regulations EN 1996 (Eurocode – 6) and accompanying regulations* (2006) and (2007) covered the topic of simplified design of non-reinforced masonry structures. Durability of structures is topical globally and nationally. The Convention *Civil engineering and sustainable development* was dealing with different thematic segments, and some of them were exceptionally important for our country such as *Designing* *engineering structures from the aspect of durability – extension of their service life*. Conference *Masonry structures – bearing capacity, durability and energy efficiency* was held on 24th November 2010. The list of papers presented at these conventions was given in [10]. Some papers of the participants were printed in the proceedings and mentioned further in the text.

General reports written by researchers were appointed in advance and submitted at all organized conferences. Some of them, who participated several times should be mentioned: Dobrosav Jevtić, Milan Krstić, Boško Petrović, Miloš Marinček (Ljubljana), Ljubomir Jevtović, Borislav Zakić and others. More details were given in [37].

12th Congress 1966 (Sarajevo): *About testing pre-stressed structures using the photo-elastic method* (V. Brčić and A. Pakvor); *Effects of high temperatures on characteristics of steel for pre-stressing and Influential diagrams for determinations of moments and deformations created due to pre-stressing and other influences* (D. Jevtić); *Stress and strain state testing on dams using models*, (L. Jovanović); *New possibilities of design of reactor casing of pre-stressed concrete in nuclear power plants* (B. Žeželj). Presentation of bridges: *Road bridge of pre-stressed concrete across the Neretva near Rogotin on the Adriatic highway* (D. Čertić) and *Construction of the bridge across the Bay of Šibenik on the Adriatic highway* (I. Stojadinović). Research results: *Towards an analysis of phenomena and behaviour of loaded structures* (M. Ratajac); *Some pathological phenomena in concrete structures of bridges* **(**B. Zakić); *Control and safety of tall dams* (B. Kujundžić and L. Jovanović). General report was submitted by M. Krstić (as mentioned previously).

13th Congress 1969 (Bled): Model studies of a nuclear reactor casing of pre-stressed concrete. *Tests by photo-elastic method and application of photo-elastic coatings* **(**V**.** Brčić with the associates from the institute "Jaroslav Černi"); *Contemporary fundamental research in the continuum mechanics and potential for application in our civil engineering* (R. Stojanović from Faculty of Mathematics); *Constants of stress couples* (S. Ranković); *On the remediation of several buildings by pre-stressing* **(**D. Jevtić and B. Vojinović). General report on theoretical and experimental research of the structures was submitted by D. Jevtić.

14th Congress 1972 (Haludovo-Krk): *Testing pre-stressed beams and cross sections exposed to limited torsion* **(**M. Muravljov); *Redistribution of effects of the linear systems from pre-stressed concrete* **(**D. Jevtić and V. Mihajlović); *Time distribution of impacts under the action of stress creep of concrete* (Đ. Lazarević et al.); *Influence of extremely short-term loading on the behaviour of pre-stressed concrete structures* (D. Jevtić et al.); *Ultimate bearing capacity of locally loaded concrete elements* **(**M. Ivković and M. Aćić); *Stiffness of concrete and reinforced-concrete beams at torsion and normal force before and after the onset of cracks* (R. Vukotić). General report was submitted by V. Simović.

15th Congress 1975 (Ohrid): *Fatigue resistance of laminated glued structures made of poplar wood timber* (B. Zakić); *Influence of flow and shrinking in the cross sections of RC beams* (M. Ivković and Ž. Perišić)**;** *Towards the research of parameters of transverse deformations of concrete from the aspect of integral relations between stress and strain* (M. Muravljov); *Extreme values of stress in composite structures* (J. D. Lazić); *Parametric resonance of simple beam of highly elastic material* (V. B. Lazić); *Some issues regarding dynamic testing of bridge models* (M. Radojković)**.** General report on concrete structures research was submitted by D. Jevtić, and on steel structures by M. Radojković.

16th Congress (Vrnjačka Banja): *Viscoelastic deformation of thin-walled member of open profiles of pre-stressed concrete tensioned to limited torsion at loading and unloading* **(**M. Muravljov); *Potential of generalization of relation between the stress and strain of concrete* (V. Mihajlović); *Diagram of stress of compression in cross-sections of RC beams with cracks due to long-term loads* (Ž. Perišić); *Some results of experimental tests of reinforced-concrete rectangular beams loaded by combined bending moment by torsion and transverse force (M,T,Q)* (R. Vukotić); *Equations of the moment of failure of timber beams submitted to torsion and axial force* (B. Zakić); *Ultimate stress values in concrete for the flat state of stress*, M. Aćić; *Limit bearing capacity of locally loaded concrete elements* (M. Ivković); *Scientific research support to the open industrialization of housing buildings* (B. Žeželj); *Recommendations of new regulations for testing of reinforced-concrete and pre-stressed structures of the Committee TBS-20-Rilem* (B. Zakić). General reports were submitted by D. Jevtić (BK-CS), S. Ferušić (MK-SS) and M. Velkov (seismic).

17th Congress 1982 (Sarajevo): *Experimental examination of thermal in-compatibility of the concrete components* (S. Venečanin); *Analysis of stress and strain of pre-stressed TT beams* (R. Folić); *Limit bearing capacity of complex reinforced-concrete cross-sections at symmetrical bending* (V. Mihailović)**;** *Influences in statically indeterminate reinforced concrete structures caused by time displacement of support points* (M. Muravljov); *Influence of yield on the curve of eccentrically compressed RC elements in stress state I* (Ž. Perišić)**;** *One procedure for calculation of stress in the cross sections of composite systems* (M. Ivković and M. Đurđević)**;** *Influence of non-tensioned reinforcement on the force losses of the pre-stresses* (Ž. Perišić and V. Alender). General reports were submitted by B. Petrović (CS), Lj.Jevtović (MS) and B. Zakić (timber structures).

18th Congress 1986 (Portorož): *Experimental research of behaviour of RC beams at short-term loads* (D. Bajić)**;** *Towards a study of ultimate states of RC T-beam* (R. Folić**);** *Analysis of concrete yield in homogenous RC linear structures applying the force method* (D. Najdanović); *On the pre-stressed metal structures and on the welding of cold-rolled profiles* (Buđevac et al.). General reports were submitted by B. Petrović (CS), M. Marinček (MS) and B. Zakić (TS).

19th Congress 1990 (Novi Sad): *Testing results of laminated glued timber beams after long-term action of load* (B. Zakić et al.**);** *One of theoretical-experimental approaches to determination of elasto-mechanical characteristics of timber* (M. Gojković et al.). *Presentation of basic parameters of calculation of timber structures according to limit states* (B.

Stevanović and S. Vasić); *Energy aspect of behaviour of hollow brick panels reinforced with RC grillwork-grid* (R. Folić et al.); *Influence of caple beams on the behaviour of RC walls with openings under seismic load* (S. Žorić and R. Folić). General reports were submitted by B. Petrović (CS), T. Nikolovski (MS) and B. Zakić (TS).

20th Congress 1996 (Cetinje): *On matrix modification of stiff joints, in frames, into flexible node joints* (D. Bašić et al.); *One numerical procedure for designing anchored support structures* (M. Lazović); *Bearing capacity of piles loaded by vertical compression and design of settlement of foundation slabs of finite stiffness* (D. Milović and M. Đogo); *Determination of the class of cross sections according to Eurocode 3* (D. Buđevac et al.); *Design of profiles of aluminium alloys from the aspect of local stability of the cross-section element* (B. Gligić); *Basic characteristics and calculation of composite beams of timber and concrete* (B. Stevanović); *Design of composite columns* (B. Deretić-Stojanović); *On the ultimate bearing capacity of horizontally loaded frames* (R. Đorđević); *Longscrew design for composite beams* (N. Marković); *Verification testing of members and nodes of spatial steel structure* (D. Buđevac et al.); *Methodology for assessment of bearing capacity and reliability of existing railway bridges* (M. Pavišić); *Assignment of the status of silo cells for soy and grains and analysis of some test results under test load* (R. Folić, V. Radonjanin, M. Malešev). General reports were submitted by A. Vujović, R. Pejović and M. Ulićević (CS), G. Srećković (MS), B. Zakić (TS) and V. Brčić for theoretical analysis of structures.

21st Congress 1999 (Belgrade): *Determination of indicators of deformability of soil for analysis of interaction with shallow foundations (I): modulus of soil reaction and equivalent elastic soil constant* (M. Samardaković); *Soil-foundation interaction – incompressible substratum* (D. Milović and M. Đogo); *Procedure of formation of matrix equation of the foundation girder of variable cross section arbitrary loaded on its ends* (V. Prolović et al.). *On the assessment of the status (condition) of the Theatre building in Subotica and other structures* (S. Grković). General reports were submitted by S. Venečanin (CS), D. Buđevac (MS), B. Zakić (TS) and M. Milićević for theoretical analysis of structures.

22nd Congress 2002 (Niš): *General theory of laminate slabs – analytical solution for simply supported slabs and Composite slabs with delaminations – analytical solution for simply supported slabs* (Đ. Vuksanović, and M. Rakočević); *Calculus of bearing capacity moment of the composite cross-section to lateral torsion buckling according to Eurocode 4* (B. D. Stojanović); *Influence of differential shrinking on the stress state in the cross sections composed of two concretes of different qualities* (S. Mašović); *Non-linear dynamic analysis of structures exposed to action of impulse earthquakes* (Đ. Lađinović); *Aspects of the choice of calculation mode for verification of structural testing results by testing loading* (Z.Mišković and Lj. Jović); *Testing of composite beam timber-concrete, constructed by mechanical connections* (B. Stevanović); *Experimental testing of self-tapping screws loaded to tension* (Z. Marković); *Products on the basis of carbon fibres – tests and application* and *One example of application of carbon strips for rehabilitation of RC structures* (M. Muravljov);

23rd Congress 2005 (Novi Sad): *Research of seismic reliability of old masonry buildings in Belgrade* (N. Stojanović et al.); *Finite element based on the general laminate theory of plates* (M. Ćetković,Đ. Vuksanović); *Some dynamic actions on foundations and dynamic properties of soil* (B. Folić and R. Đorđević); *Design of structures of timber prefabricated housing in seismically active areas* (T. Kočetov-Mišulić et al.); *Influence of history of loading on the ultimate limit state of pre-stressed elements cracks* (B. Popović); *Remediation of beams of glued laminated timber with carbon strips* (M. Komnenović and B. Stevanović); *RC elements exposed to bending, strengthened with additional concrete and FRP (fibre reinforced polymer)* (R. Folić); *Comparative methods of analysis of reinforced concrete beams strengthened with FRP* (R. Folić and D. Glavardanov). General reports were submitted by R. Pejović and D. Najdanović (CS), Z. Marković (MS), D. Stojić (TS) and Đ. Vuksanović for theoretical analysis of structures.

24th Congress 2008 (Divčibare): *Application of elasto-plastic models for soil in calculation of geotechnical constructions FEM* (M. Vukičević); *Approximate calculation of slender RC columns bended in two axes* (Z. Brujić); *Static treatment of concrete structures with effects of long lasting loading* (S. Mašović); *Dynamical behaviour of wooden ceilings (floor structures)* (B. Stevanović and I. G.); *Maintenance models of concrete structures strengthened with composites-(FRP) elements* (R. Folić and D. Glavardanov).

25th Congress 2011 (Tara) and International Symposium: About research and application of modern achievement in civil engineering in the field of materials and structures. Papers: *FEM modelling in assessment of real structural behaviour* (D. Kovačević); Actual approach to shear design of the prestressed and reinforced concrete beams (B. Popović); *Models of failure of NSM strengthening method of RC beams-experimental research* (S. Ranković and R. Folić); *Pile integrity testing SIT method- theoretical basis and case study* (D. Berisavljević and N. Šušić); *Analysis of stainless steel members in axial compression* (J. Dobrić et al.); *Reinforcement of wooden laminated beams with carbon strip* (R. Solarov et al.); *Optimal design of rectangular RC cross-sections subjected to uni-axial bending according to EC 2* (Z. Brujić); *Modelling multy-storey RC frames for nonlinear static pushover analysis* (A. Radujković et al.); *Determination of embedding strength of wood for material dowel type fasteners* (B. Stevanović et al.).

## 4 Research work at Faculties until 1976 and after 1976

### 4.1 Research work at Faculties until 1976

It is very difficult to make periodization regarding the scientific work (SW) at FCE in Belgrade. There is a quotation in [44] that the faculty used to be almost exclusively an educational institution until the WWII and even to 1960s. Scientific work of teaching staff was mostly individual and certain number of scholars took part in activities of other institutions, for instance, Institute "Jaroslav Černi". It was only in 1960 and 1970 when the laboratories were founded and started cooperation with industry, while the scientific work was still individual. In 1976 the Republic began funding the Faculty for three to five years lasting projects.

There is no doubt that at the very beginning academics Ivan Arnovljević and Jakov Hlitčijev, and later academics Đorđe Lazarević, Milan Đurić and Nikola Hajdin shaped the development of the Theory of Structures (Construction). Significant influence was made also by professor Vlatko Brčić, especially with his monograph *Structural Dynamics* [5], Milorad Ivković with his dissertation: *Concrete behaviour in the domain of the limit equilibrium* (1962) and Miodrag Sekulović, with the book FEM [46] at first and then with non-linear analysis of structures [47]. Academic Đ. Lazarević was the initiator of basic as well as applied research and monograph of M. Đurić *Theory of composite and pre-stressed concrete structures with original contributions to analysis of those structures* (SANU, 1963) by applying time deformations of concrete which was widely used in designing and had strong influence on younger scientists and designers of such structures.

Some of the results of individual work were widely applied in structural analysis, too. Such is, for instance, integral equations method N. Hajdin applied in calculation of arch dams. Our science was also affirmed by papers related to application of the method of holographic intereferometry in photo elasticity by V. Brčić (Udine-Itali). Papers of V. Bogunović about the slab flexion and elastic stability of slabs and grillwork were published abroad.

The condition of plastic-failure of concrete which was presented by M. Ivković according to his experiments and results gathered from other researchers still enables applying the theory of plasticity while solving the problems of limit equilibrium. Research work of D. Radenković is dealing with the problems of soil mechanics, e.g. determination of soil bearing capacity.

The monograph of Đ. Lazarević: *Slender segmented arches as one fold and stepped multiple systems of dams* and *Stress calculation of eccentrically loaded ring cross-sections* and many other papers regarding these problems, enriched applied theory of structure (constructions) and influenced the development of modern approach to the calculation of complex constructions in a domain of limit state and optimum dimensioning. He enriched the topic as well as profession with his papers [48]. By model research of parabolic hyperbolic shells of A. Božanović it was proven that deflection of a compressed field of hyperbolic surface turns two axial system into one axial tensioned stress system on the biggest part of the surface. It should be noted that M. Trojanović by publishing four books about concrete bridges established the theoretical grounds for analyzing these structures (book one and two) and the books three and four provided the analysis of chosen examples of bridges performed by RC and PCS. With his books he significantly influenced the establishment of the Belgrade school of concrete bridges which resulted in many outstanding achievements.

Apart from the mentioned contribution M. Đurić developed the general method of deformations in statics, stability and dynamics of structures with wide practical application. His doctoral dissertation is one of the first papers with matrix calculation application.

Papers of N. Hajdin and M. Sekulović with Kolbuner, were published in two monographs about founding (numerical analyses of beams, grids and plates on elastics ground, and for analysis of diaphragm embedded in elastic semi infinite space/body). In addition, the paper of Ž. Radosavljević about calculations of a group of piles was especially prominent. The papers of Stevan Stevanović in the domain of founding were outstanding as well.

The papers of Jakov Lazić about highly elastic models [39], M. Sekulović about thin-walled rods and FEM application are significant. Calculation of building structures under the earthquake effect (D. Dimitrijević), then structure-soil interaction (M. Manojlović) are noteworthy as well as the research of calculation methods of arch dams with statical models of dam testing on spatial models in elastic domain and failure. He performed the verification of a dynamic calculation of dams in situ on Zlatibor and Modracu (BiH) dams. In relation to these problems the mechanics of rocks and geotechnics were studied in significant papers of P. Anagnosti and R. Stojadinović with associates.

Professors Živorad Radosavljević and Branislav Kujundžić with associates in Institute "Jaroslav Černi" developed methods of designing hydro technical tunnels under pressure. The results of this study were two published monographs: *Grouting of hydraulic engineering tunnels and shafts under pressure* and *prestressed lining of hydraulic engineering tunnels under pressure.* In Bulletin No. 3/60 B. Kujundžić wrote a paper about observing tall dams.

### 4.2 Research in Serbia and Vojvodina after 1976

Scientific projects over the period from 1976-1995 were conducted mostly in cooperation between Institutes for materials and structures at FCE and Institutes "Jaroslav Černi" and "Kirilo Savić" as well as with FCE and Faculty of Occupational Safety in Niš. Projects covered a wide domain of technical sciences with a potential for individual engagement. These projects were carried out through fully individual work and organized research in this domain with aims clearly determined. The following projects were conducted:

1. *Contemporary problems in research of structures* ( Milan Đurić);
2. *Theoretical and experimental methods of testing and researching of structures, materials and building environments* (Vlatko Brčić);
3. *Contemporary problems of materials, constructions and environments in Civil engineering* 1986-1990;
4. *Plasticity and stability of steel structures* 1991-1995 (Nikola Hajdin) and later (Miodrag Sekulović) as basic science project.

In the project No. 4, steel structures were studied in domain of plasticity and stability of equilibrium regarding the influence of research on the practice of design and performance. The project included the following subprojects:

1) Comparative study of scientific results in a domain of plasticity and steel structures stability and their influence on the change in standards and regulations

2) Plasticity and stability of the system with application in steel structures of buildings, with the following topics: Plasticity and stability of frame beams, ultimate capacity of rigid angles in a beam-column connection that is made by friction grip bolts and front plates; Boundary bearing capacity of structures in building including effects of diaphragms made from profiled sheets; Performance and protection of steel structures from effects of high temperature

3) Plasticity and stability of metal sheets of solid and rectangular girders with the following topics: Application of FEM on study of post critical stadium of thin sheets and ultimate capacity of solid and rectangular girders; Experimental and theoretical research of lateral stability of solid girders with or without stiffening that are exposed to the effect of concentrated load; Ultimate capacity of I girder with thin web which is exposed to repeated loads; Geometrical imperfections of sheets on constructed structures; Study of ultimate load capacity of thin-walled girders with open and closed profiles

4) Plasticity and stability of metal shells with applications included the following topic: The performance of steel shells with stiffeners and ultimate bearing capacity of cylindrical shells formed of corrugated sheet with or without stiffeners. Certain number of topics regarded fundamental features and the other topics were based on practical experience of fire consequences on steel structures of buildings and imperfections in constructed structures, which formed a base for further analysis. Part of the results from this project was presented at *International conference of steel structures* (Budva, 1986.). Project No. 3. included four topics: 1) Elasto-plastic and limit analysis of metal structures and their optimization; 2) Methods and models of numerical analysis of structures; 3) Theoretical researches in the domain of management and economics of building production and 4) Methodology of stress-deformation analysis and limit equilibrium for non linear constitutive connections and non linear criteria of failure in soil and rock mechanics. The obtained results for topics 1 and 2 were presented at symposium *Contemporary problems of non linear analysis of structures* in March 1993. The monograph was published [47] as well.

From the scope of mentioned projects several master papers and doctoral dissertations were published.

The fundamental research and technological development research have been financed in Vojvodina since 1975, as well as the development of scientific disciplines directly related to the narrow scientific fields which were studied over the period of three years. The author of this paper headed the project: The theory of concrete structures and its application in concrete structures – The development of scientific disciplines (1988 – 1990). In the field of fundamental research the focus was on the development of the joints and connection system in prefabricated building constructions and engineering structures. This was due to the orientation towards the prefabricated constructions (industrial building). The behaviour of the concrete constructions with developed layout under the durable effects was studied as well. The research from the field of Construction management was financed too, and it was supported with the funds of Chamber of commerce of Vojvodina. At that time many minor themes were researched for the Federal Chamber of commerce, and those mostly lasted a year. This contributed the affirmation of the researchers and younger associates in spite of limited funds. Better research financing started in 1985.

The projects from the field of constructions:

1. *Research of concrete and masonry structures under the dynamic load and structure-soil interaction* (1985-1990) head R. Folić.
2. *Research of the principle of design of the structures exposed to impact loads* (1986 - 1990). (V. Vračarić and R. Folić). The project was done for the National Defence.
3. *Research in the field of the design of supporting structures of electro-mechanical transmitters* (for the use of the company "Sever" Subotica, 1988/89 (R. Folić)
4. *Development of construction system of prefabricated timber houses "Špik" Ivanjica* (1994-1995) (R. Folić).
5. Joint research with the University of Berkley since 1985-1989 on a YU - USA project: *Research of the system of joints and connections of prefabricated large panel concrete buildings in seismic areas* (B. Petrović and R. Folić)

**Over the period from 1991-1995** merging the Republic and Regional Scientific Communities led to the gathering of great number of FCEs and IMSs scientists around projects. The organization was superb and the Ministry kept track of the work and the results of the projects. At that time it was habitual for the heads of the projects to write an overview in which they showed the results of the research. This was serious and public verification of the achieved results. Recently, the poster presentations have been introduced into practice, which is considerably lower level of verification. There is only a part of the results showed in the overview for the Project No. 1721: *The research of the elements and structures from the aspect of bearing capacity, serviceability and durability, including the revitalization of the buildings* [23].

The paper [23] shows goals, structures and general results of the scientific research project. The research of bearing capacity, durability and serviceability of the elements and constructions; studying of the behaviour of certain engineering structures and bridges in situ and in laboratory; methods of maintaining, remediation and revitalization of concrete, wooden and steel structures; studying of the behaviour of machine and facility foundations, concrete and masonry structures under the dynamic load, as well as the application of the theory of plasticity, stability and numerical procedures in the analysis of elements and concrete, wooden and steel structures were included. In five research years more than 200 papers were published.

Extended theoretical and experimental research was undertaken in order to better understand behaviour of elements and constructions under diverse kinds of load. This was also important for finding adequate ways of designing, building, maintaining and remediation of building structures and constructions. In the course of this process many different problems of contemporary timber, steel, concrete and composite structures were explored. This was also done with different methods and types of analyses of elements and structures in order to adjust them to contemporary problems of structural engineering and enhance them. Many designing regulations given in International societies and Eurocode recommendations [6] were studied, in order to make a theoretical basis for their easier application.

The following issues were studied:

- Bearing capacity, serviceability, durability and revitalization of concrete structures,
- Research of concrete constructions and masonry under the dynamic load,
- Theory of plasticity and problems of contemporary constructions stability and
- Analysis of the steel and concrete structures and large span bridges behaviour.

The themes overlapped in many aspects since they all emerged from the common goals. Those were creation of new elements and constructions with optimization of their silhouettes, which would satisfy not only economic standards but also the needs of safety (bearing capacity, serviceability, durability and maintenance). This led to the fact that after the second year the project was treated as a single set of research tasks.

The influence of the load history on limit states of serviceability of RC and pre-stressed structures was studied. The procedure of strain state calculation in the cross sections for discontinuous actions was proposed, including the change of the active part of cross section after the onset of cracks, applying the constitutive connections of integral type. The procedures for calculation of deflection of partially pre-stressed elements were analyzed, and the procedure of ultimate state of crack openings and their behaviour after decompression was introduced. Apart from that, differential relations, i.e. Maxwell model for the state of stress and change of strain in concrete were used for the analysis of stress and strain state in RC and partially pre-stressed elements. The same model was used for the analysis of limit serviceability state in partially pre-stressed elements. The properties of the relaxation function and concrete aging coefficient obtained numerically on the basis of the concrete flow function according to Model Code 1990 and EC 2 were analyzed. Interaction diagrams moment – normal force – curve for the calculation of slender RC elements “column model” were designed.

Starting from the interaction of architectonic and structural designing, contemporary structures in high rise construction were analyzed as well as the choice of the systems for stiffening high rise buildings. Structural systems of prefabricated timber panel houses (PTH), were applied here, with the focus on testing basic materials, elements and connections. A parallel with the recommendations of EC5 is emphasized for the calculation of basic elements of PTH. The methodologies of assessment of structural status, material testing, causes of damage and remedial measures of specific timber structures were proposed. The report of the state of affairs in the area of composing timber beams and concrete slabs was produced. The theory of composing was presented with and without introduction of slipping between the layers. A number of issues regarding specific structures of foundations under the dynamic loads, that is, foundations of machines and various industrial facilities were treated (published monograph, R. Đorđević). The report of the state of affairs in many topical areas of structural engineering treating the issues of bearing capacity, durability, serviceability and maintenance of engineering structures, as well as the behaviour of elements and structures under variety of loads was submitted.

In order to include the yieldability (semi-rigid) nodes of prefabricated RC frames, the matrix of stiffness of members with the arbitrary level of fixation was developed, and the method of determining the semi rigid of corners was demonstrated. Through the numerical analysis, it was demonstrated that the redistribution of moments occurred between the cross sections in nodes and in the span, as a consequence of semi-rigid nodes, so it could not be ignored, when it came to prefabricated concrete structures [24]. It is important to mention, that in this area, the initial impulses were given by M. Đurić (INDIS, 1976) and M. Milićević (17th Congress of theoretical and applied mechanics, 1986) from Niš. In their work, they treated static analysis, stability and dynamic analysis. In the process, they used the classic strain method approach. For timber structures, the matrix analysis was developed by D. Bašić, D. Stojić and E. Mešić, and for steel structures by M. Sekulović, B. Ćorić and R. Salatić. This theme is still topical and researched both locally and globally.

Within the project *Development of scientific disciplines* which was financed by the Scientific fund of Vojvodina, the work on research of semi-rigid of joints of prefabricated large pane buildings was continued. The paper was published in 2001 [26]. In the paper, the effects of semi rigid of joints of concrete large panel buildings (LPS) with the accent on the semi-rigid of joints of walls were analyzed. For the analysis of bearing and stiffening walls and mixed systems skeleton-bearing walls the Finite elements method (FEM) is used for their analysis. Stiffness matrices used for the calculation of walls with yieldable nodes were given. At an example of a diaphragm between the RC columns of ten-storey buildings, the results were compared assuming the stiff connection of the columns and diaphragm and assuming that columns are stiff and diaphragm joints yieldable. The effects of redistribution of stress $\sigma_y$ at the bottom of the diaphragm due to semi-rigid of joints were presented. It was demonstrated that this phenomenon should be included in the calculus for concrete prefabricated buildings so as to describe their behaviour under load in as realistic manner as possible.

It was very important for Structural engineering that for a long period of time, especially until 1993, many scholars and associates professionally engaged in Technical mechanics and Theory of structures took part in the realization of fundamental research. Those activities were coordinated through The Institute of Mathematics of SANU. Thanks to this fact the author of this text headed the theme from the area of Structural dynamics from 1991 to 1993. The same year many difficulties appeared when the Ministry of Science insisted on separating the fundamental and technological development research, thus preventing simultaneous work on both of them.

Scholars and associates, mainly from the field of Concrete structures from Serbia, were gathered around the realization of the research program of the Project: Research of Concrete Structures (1996-1999). The program was very extensive as well as subprojects, which can be seen in the title of the one headed by the author of this paper: Modelling the materials, connections, structures and soil behaviour as well as soil and structures interaction under static, dynamic, seismic and incident actions and during the fire. The researchers from Novi Sad, Beograd, Niš and Subotica took part in realization of this project. Here are some results:

– The problem of structures interaction – foundation – soil with special foundation structures like consoles and anchoring diaphragm walls was studied. Linear and non linear analyses were used;

– Introduction of structure interaction – foundation – soil, in order to improve the method of constructions and foundation structures design;

– Methods of concrete composition, working of contact surfaces and calculating procedures for cross-section with and without cracks, and with introduction of concrete shrinkage and yield were studied;

– Introduction of new methods of calculation and concrete composition structures modelling;

– Further analysis of static and dynamic behaviour of special structures in order to improve large span structures design;

There are some other projects on which predominantly worked the researchers from Vojvodina, and which were financed from Republic funds:

- The subproject: *EC 8 – Designing seismically resistant structures* in technical project: *Introducing the Eurocode system and adopting the new methods of designing products and technologies in Serbian structural engineering* (1995 - 2000), Head of the subproject - R. Folić.
- *Preparation of new regulations and instructions for Eurocode applications for structures in our civil engineering* (2003-2005.) – Subproject: *EC8 - Designing seismically resistant structures*; Head of the subproject R. Folić
- *New technologies in research, designing, building and service managing of engineering structures* (2003-2005), Head of the project R. Folić, coordination IMS Beograd.
- *Improving inspection, assessment, revitalization and reconstruction of structures methodology*, Ministry of Science, Technology and Environmental protection of Serbia, (2005-2008) Head of the project R. Folić.

It is important to mention the work of the researchers from Belgrade, Novi Sad and Niš Faculties on technological-development project: *Introducing the Eurocode and adopting new designing methods*, headed by Ž. Perišić. The work lasted from 1993-2000 and it continued in 2005 with the translation of the EN 1990 – 1999 document, and introduction of Eurocode into our practice (which was given recognition of merit by the Engineering Structures Society DGKJ for the best scientific work in 1996/7). The author of this paper headed the Subproject: *EC 8 – Seismic Design of Structures*. The task of introducing the European standards into our practice was taken seriously, owing to the contribution of professor Života Perišić. This is evident in the fact that two Meetings regarding this Project were held in 1995 and 1997: Eurocode and Constructive Engineering. The interest was great and the attendance enormous. This period of activities was focused on Pre-standards prEN, not towards EN being published in 2002: EN1990, until 2006. It is also important that we took part in many Congresses organized by Macedonian Constructors Society with introductory papers, such as [25].

The research from 2008 – 2010 was grouped in the following projects:

- *Experimental and theoretical research of real connections of reinforced concrete and composite structures under static and dynamic load* (B. Stevanović);
- *Research of contemporary concrete composite based on domestic raw materials with the focus on potential of applying concrete with recycled aggregate* (V. Radonjanin);
- *Development and improvement of engineering structures exposed to seismic and incident actions design* (Đ. Lađinović);
- *Research of long-term and short-term monitoring methods in engineering structures* (Z. Mišković);
- *Experimental and theoretical research of dynamic characteristics of pre-fabricated and semi prefabricated structures and elements from the aspect of serviceability* (B. Stevanović);
- *Safety, bearing capacity and stability of composite and steel structures in housing and bridge building and new technical regulations* (B. Ćorić).

### 4.3 Experimental and theoretical analysis of T Beam

Since many authors presented some of their papers, the work on the doctoral dissertation is presented here, as well as some later studies. This is the summary: The paper deals with experimental and theoretical research of RC concrete T-beams. Relation between width of the flange and span of girders, quantity of tensile reinforcement in longitudinal webs and occurrence of edge cross ribs to behaviour of T-beams under loading have been experimentally and theoretically studied. On the basis of personal investigations and cited data, the determination of the effective width of flange subjected to bending, torsion and normal forces is considered. Data about cracks and deflections of reinforced concrete girders are given. It is shown that relation between width of flange and span has a dominant influence on effective width of flange, while quantity of tensile reinforcement in webs has an important influence on limit state of serviceability with reference to deflections of girders.

Permanent usage of T-beams in concrete structures led to their thorough study. They can be found in monolithic and pre-fabricated construction as a combination of planar structure and beam elements, most frequently flange-web, and the box girders can be processed by the same calculation model. These girders can be exposed to bending, torsion, normal forces or combined action. However, under the term of T-beam we usually think of the elements exposed to bending. Almost all the time the linear theory of elasticity is used for influence calculation of these beams. In case of the statically indeterminate structures, the stiffness of the elements is introduced. Although the stiffness depends on the reinforcement method and condition of the cracks, it is designed for homogeneous cross section, so it is particularly important to define the cross sections as accurately as possible.

When the spacing of the webs is large, the distribution of normal stresses is not uniform, i.e. the stresses $\sigma_X$ which have the highest value at the flange/web intersection and taper off with the distance away from the joint. Therefore, it is necessary to determine to what distance from the web, in load distribution, there is the interaction from the slab (flange). Thus a phrase "effective flange width" (EFW) is defined. The actual width of the slab is substituted with the smaller width, with which the value of "the highest normal stress $\sigma_{X,}$ occurring at the contact of the slab and the web" can be correctly calculated. The distributions of stress in the flange and in EFW are determined by theoretical numerical analysis and/or experimentally. There are presented and analyzed some of the results of experimental and theoretical research of T-girders of reinforced concrete and rectangular girders of pre-stressed concrete under short-term load. Analysis of limit states relates to the serviceability states of RC girders, that is, except the EFW, the cracks, deflections are considered as well as the problem of the slab-web joint and stability of the flange.

For the purpose of the study of T girders, 7 RC models were tested and tow pre-stressed rectangular girders, under test load, until failure. The chosen form of RC model allowed analysis of two boundary cases: T-girder with cantilever slabs $b_2/b_1 = \infty$ and Π-girder with the internal slab with $b2/b1 = 0$. On all the girders longitudinal strains $\varepsilon_X$ on the upper surface of the slab were measured in the transversal direction and along the cross-section height, and on RC models and in tensioned and compressed reinforcement. The deflections were measured at 1/6 of the span on the longitudinal webs, and at ½ of the span in the girder axis and at the ends of cantilever slabs. Onset and development of cracks were recorded for each phase of load.

The load was applied by the hydraulic press "Amsler" over the axis of the web, by a pair of symmetrically positioned forces. Design load was applied in four uniform phases each being 25% of service load.

To achieve full economic effect, it is necessary to achieve equal resistance of individual component parts until the ultimate state is reached. Therefore, a part of experimental results is focused on the study of ultimate states. The number of parameters that could vary in these calculations is high, but the program described here included only the most dominant ones. The following were studied:

- Effects of geometry of RC models expressed by the ratio of spacing of longitudinal webs and span of the girders,
- Quantity of tensioned reinforcement in longitudinal webs, and
- Existence of end (lateral) webs.

In order to study the influence of the quantity of tensioned reinforcement in the webs, the first batch of models was concreted with 3 rebars ø 16mm (1.54%), and the second batch with 6 rebars ø 16mm (3.24%) of RS 400/500. Thus, 6 RC models with end transverse webs were obtained. One girder was without end transverse webs. In order to check the validity of the solution of the theory of elasticity, the results of the experiment were compared to the results of the analytical solution of the theory of elasticity, finite element method and final strip method. In the theoretical analyses, linear theory of the first order was used.

The following assumptions were introduced:

- Thickness of the flange and longitudinal webs are significantly smaller than other dimensions, so bending of the flange is ignored, and flanges and webs are tensioned only in their planes and mutually connected along the lines on the intersection of the centreline of the flange and the web, where the deformations must correspond;
- Longitudinal webs receive the load in their planes; and Transverse girders are stiff in the direction of their centre plane and prone to bending perpendicular to that direction.
- The forces acting in the centre plane of the flange are predominant, and can be found in the equation:
- Longitudinal strain of common fibres of the flange and the beam in the centre plane of the slab,
- The curves in the centre plane of the slab and the beam in the centre plane of the slab.
- The curve of common fibres in the plane normal to the centre plane of the slab,
- The rotation of common surface of the slab and the webs.

Applying the finite element method, the effects of the type of load and end transverse webs on the stress and strain state is examined. The structure is idealized with the set of rectangular elements loaded in their plane, and mutually connected in the nodes. It is assumed that the stress is linearly distributed within the rectangle, and the resulting distribution of displacement satisfies the compatibility conditions, only in nodes.

In order to compare the efficiency of various methods and study of the surface load on the slab in respect to the equivalent linear load on the longitudinal webs, the finite band method was used.

Effective flange width of a T-beam exposed to bending depends on a number of parameters related to cross section and loading. The most important are:

- Ration of the flange width and span of the beam $b_1/l$ or $b_2/l$, where $b_2$ is the width of the console slab, and $b_1$ is the ½ of the spacing between two webs,
- Static system, that is, support conditions and position of the cross section where the effective width is calculated,
- Types of load (uniform distributed, concentrated etc.),
- Shape the form of the cross-section, and
- From the fixing conditions at the ends of the beam (degree of securing the beam against torsion).

The percentage of tensioned longitudinal reinforcement has no significant effect on the average value of EFW. Apart from that the experimental research of AB (RC) girders are limited by the scope and varied parameters. They are combined with theoretical analyses, and enable recommendation of the simplified expressions for determination of EFW. The expressions are analyzed in detail in the book [45].

Comparing the size of the effective flange width under bending achieved experimentally on the full scale models, and theoretically by the application of linear theory of elasticity, acceptable compatibility was obtained in almost all the cases. Somewhat higher values were obtained in experimental research. So it can be concluded that for determining the effective width of RC and pre-stressed girders the linear theory of elasticity may be applied, because the calculation results are on the side of safety. Out of several varied parameters, the influence of the flange width and spacing the zero points of moments is important for the effective width, and the quantity of tensioned reinforcement in the webs is almost negligible. The favourable effects of end transverse webs on the effective flange width in the zone near the supports were observed. A higher quantity of tensioned reinforcement of the longitudinal webs results in economical T-beams with wide flanges, from the aspect of stress usage, but it is necessary to ensure that the limit states of deflection are not exceeded. Existence of end transverse webs has a positive effect on the behaviour of T-beams with wide flanges, both from the aspect of the stress and the aspect of development of cracks and deflections, so they should not be deflected, unless it is really necessary. In the book [45], the recommendation for inclusion of torsion is given along with normal forces when determining the effective width of the flange.

## 5 Analysis of structures

Beside the experiments, numerical analysis of structures is always a theme of interest in structure research. Development of computers and their mass usage, especially in the last 50 years, enabled considerably more accurate analysis of engineering structures under mechanical, thermal and other action. Computers changed the way of calculation and enabled the development of modern numerical methods which can be applied in research and design. Finite element method (FEM) due to its simplicity, mathematic basis and clear physical meaning pushed aside other methods. M. Đurić provided valuable contribution to the application of theoretical results in practice in the field of composite and pre-stressed structures; V. Brčić in the field of structure dynamics and M. Sekulović for application of FEM in structure analysis.

For the design of engineering structures different approaches are used. Firstly, global analysis of structures is done and then analysis of its elements and cross-section. The design according to permissible stress is abandoned except in the case of pre-stressed and composite structures. Since it was necessary to provide safety in the case of failure as well as serviceability, the concept of design according to ultimate limit states was generally accepted. These are the states limited by some value the structure should not exceed according to the requirements the structure should meet in its service life. The most important of all mechanical properties of material is its relation stress – strain (working diagram) and therefore, theory of elasticity and theory of plasticity are used in the design. In addition, very important is the type of load (short-term, long-term, static and dynamic) and the influence of the environment temperature, humidity…) In the working diagram, the most important are the points of elasticity limit, beginning of plastic deformations and failure deformations.

The most complex designs are for RC structures and composite structures steel-concrete, wood-concrete, and in the last few decades concrete-concrete. It is due to the fact that concrete is a heterogeneous material, which apart from the shrinking deformations during setting also possesses the viscous properties, that is, deformations increase under constant stress in time. Geometrical structures also conditions application of appropriate models (linear, planar, and spatial) and the purpose of the structure.

For the design under the short-term stress, as it is well known, linear and non-linear analysis models are mainly used. Rise of computers and their advanced application facilitated RC structures analysis on more complex models than before, when the linear model was used. Non-linear properties of material, dominant in reinforced concrete emerged from the onset and propagation of cracks and non-linear stress-strain relation for steel and concrete and interaction of concrete and reinforcement. Non-linearity of structural relations is apart from the mentioned things a consequence of the non-linearity of the relation of bond stress and local slippage of reinforcement. Contemporary numerical models based on FEM facilitate easier analysis of real behaviour of RC structures which is particularly interesting for special engineering structures. For analysis of bended beams and planar girders under short-term loads, the models based on FEM were analyzed. For analysis of these beams, emergence and propagation of cracks, effect of bond of concrete and reinforcement, transfer of shear forces in the cracked concrete (local effects) should be studied for determination of global behaviour and ultimate load.

Three procedures are implemented: a direct procedure with classic finite elements and the material non-linearity is introduced through the effective stiffness, determined by experiments. The second procedure is with the layers of finite elements. The flat stress state defined by the biaxial relation stress – strain is assumed in the layers. The propagation of cracks along the height of the cross-section is facilitated in this way. Discretization along the height and width is used for analysis of complex stresses. The deficiency is the inability to include the emergence of diagonal (slant) cracks and shear failure, and for a more accurate analysis, a large number of layers are required. The third procedure is application of 3D finite elements. They are successfully used to analyze the beams where shearing is the key factor of concrete failure.

Constitutive relations depend on the stress state and they are based on experimental results. They do not take into account the time factor, and they describe the material behaviour: linear and non-linear elasticity theory, plasticity theory endochronic theory of plasticity and nonlinear theory of failure mechanics. The linearly elastic, non-linearly elastic, hyper-elastic and hypo-elastic model of material behaviour are based on the Hooke’s law. Non-linear connections S-D irrespective of the material properties (elastic, plastic or endochronic model) are expressed by total (secant) or incremental (tangential) form. Total formulation is limited to monotones, but for its simplicity, it is often implemented for description of non-linear behaviour of concrete at in-plane and spatial pressure state. More on this can be found in the paper by Sekulović, Vuksanović and Pujević [45] and papers by T. Tassios, and other authors who included analysis under long term load, and also in [47-48].

## 6 Topical problems and direction of future research

In order to provide the appropriate safety of bridges to seismic action, the following factors are significant: choice of the structure as early as in the conceptual design phase, modelling and analysis of the structure, as well as the formation of details. For the more significant structures such as the bridges of medium and large spans, in seismic areas, the first phase of the selection of structure, i.e. conceptual design is significant. In the last twenty years of the last century, the modern concept of seismic protection and control of structures was developed. Apart from the basic isolation, active and semi-active protection of structures is used [7]. These problems were considered in the paper [29]. The choice of isolation devices is very important, since through their application it is possible to ensure considerable reduction of seismic forces, so that the structure could even remain in the elastic area. The method of designing some of this protection in order to reduce the damage to the structure during earthquakes and providing adequate performances is topical. In the recent years, the application of integral bridges is topical, and they are gaining importance because of the higher durability in respect to the classic bridges [40].

For concrete bridges, and particularly for prefabricated bridges, the continuation of supports on bearings allows rational usage of material and better service performance, in particular the durability. The beam continuity is most frequently done by pre-stressing: it is monolithic, when all the cables are pre-stressed in situ, that is post-tensioning is applied; and non-monolithic when the prefabricated elements are used, such as simple beams, and continuity is effected on bearings by concreting the joint in situ [23].

Concrete structures (CS) are designed so that they can satisfy requirements regarding safety, serviceability, durability and aesthetics throughout their design service life. Present design procedures regarding CS required by national or international codes and standards such as Model Code Euro International Committee of Concrete (1993) now Federation Internationale du Beton (FIB), EN, ACI, RILEM, etc. are predominantly based on strength principles and limit state formulation. The durability aspect is a natural extension of classical resistance verification where deterioration effects are normally neglected. The review of literature and some recommendations are presented referring to the design of structures aiming to attain greater durability of CS. The accent is put on the theory of reliability, failure probability and service life probability. The basics of this analysis are given through the principles of performance and service life [12], and deterministic and scholastic methods using the lifetime safety factor [33].

Structures may be subjected to extreme events during their design-service life, which can lead to unforeseen consequences. Such situation may be caused by natural disasters such as strong earthquake, or from human errors (for instance gas explosion). Specific approach to designing PC building structures under seismic actions and abnormal loadings is described in [28]. Recommendations for design and interventions aimed to prevent progressive collapse in case of failure of part of structures are given. Alternative ways of load transmission are considered as well as measures for increasing the overall stability. Due to reduce the risk of progressive collapse, the following approaches, or tear combination are applied:

1. Reducing the risk of accidental loading.
2. Preventing the propagation of possible initial failure.
3. Designing the structure to withstand accidental loading.

In general, accidental loads can hardly be eliminated. In design all efforts should be made to reduce the risk of accidental loading as much as possible. Impact loads are the subject of an extensive book [3].

Prefabricated-monolithic structures represent a rational combination of prefabricated and monolithic structures, as they combine the advantages of one and the other. Their application accomplishes a high level of industrialization, savings in material and labour, faster construction and more reliable quality control of materials and workmanship. This contributes to their wide application in bridges, buildings and other structures. These structures are constructed faster in respect to those built in a classic way. Prefabricated elements substitute cladding and scaffold and accept the subsequently constructed concrete elements.

Partially pre-stressed structures (PPS) occupy the space between the classic RC and completely pre-stressed structures (PS). When the reinforcement is not pre-stressed, the level of pre-stressing equals zero (classical RC structure). The other end of the scale is when the degree of pre-stressing equals one, and those are completely pre-stressed structures. PPS structures contribute to a more economical construction of many kinds of buildings, industrial and engineering structures, and bridges [30]. This area of concrete structures is very topical and has a great importance for theory and practice of concrete structures.

Composite steel/concrete structures are used widely in modern bridge and building construction. The very large amount of theoretical and experimental research, design application and construction work has shown the efficiency and economy solution of composite structure. In [31] the current state of affairs related to design and analysis is presented based on quoted references, in steel-concrete composite structures.

It is important to mention that in the last 20 years adaptation of our technical regulations with Eurocode is topical. These standards were enacted over the period from 2002 to 2005. These documents were also used in the monograph with useful analyses and propositions. Adaptation of our technical regulations with EN is very topical, it is worked on in our country, and the submitted manuscript includes theoretical foundations and other aspects of analysis and design of composite structures harmonized with European standards. Since 2006 the Faculty of Civil Engineering completed translations of several documents, and on this occasion several seminars were held in Belgrade, Novi Sad, and Niš. Recently, the Institute for Standardization of Serbia formed the Working groups dealing with the final adoption of these documents. The lacking finances represent large difficulty to proceed. In the paper [51] it was emphasized that one of the main priorities of the ISS, as a national body of standardization, is the goal of obtaining the status of a full-fledged member of CEN. It is one of the conditions for Serbia to enter the EU.

Directive CPR 305/2011/EEC poses the conditions for putting the construction products (CP) on the market, by establishing the harmonized rules which would express performances relating to the important properties of CP and the requirement for CE designation. Among the important requirements are: mechanical resistance and stability, safety in case of fire. The following are specially considered: re-use or possibility of recycling construction waste (CW), materials and parts after demolition; durability of CW; usage of raw materials and recycled materials which do not endanger the environment. Harmonized standards represent the document basis for production of national technical regulations and codes. The difficult part is that there are insufficient data for national parameters. (snow, wind etc.).

Among 27 committees actively working in the area of civil engineering, the following ones are significant for structural engineering:

- U104- Concrete and concrete products;
- U125-Masonry structures;
- U167- Structural bearings in civil engineering;
- Engineering structures management;
- Concrete structures designing;
- Designing steel structures, steel-concrete composite structures and aluminium structures.
- Designing timber and masonry structures.

In the area of geotechnics, each alternate year, in the organization of the Association of Civil Engineers of Serbia, a scientific-professional meeting is held where the topics important for structural engineering are discussed: Models of geomaterial and numerical methods; Prediction and observation results of structures, observation method; Soil consolidation, reinforcing, grouting, geotextile and other; deep excavations and tunnels; piles, diaphragm and other technologies of foundation engineering; micro-zoning and seismic risk for the purpose of structural analysis to seismic action.

The still standing concept of seismic protection is still based on the design of the structure for the action of design earthquake (return period $T_r \approx 500$ y.). The bearing capacity of the structure is determined for the seismic forces which correspond to the given design level, determined by the application of the reduction factor (dependent on the capacity of deformation (ductility). From the concept based on the force which was valid in the 1990s, the approach was changed to the displacement, and nowadays, the concept based on performance and structural damage is very topical. Mathematical model for static and dynamic analysis of horizontally loaded tall buildings [18] is formulated in the paper. In the area of earthquake engineering analysis of irregular structures of buildings and beam bridges is very topical. In order to avoid irregularities, it is insisted on conceptual design and choice of regions for energy dissipation so that they are accessible for checks and repairs. In the case of extremely long bridges which rest on non-homogeneous layers of soil, additional separation (expansion) joints are introduced in order to avoid differential displacement.

Due to the small seismic resistance of masonry buildings, the issue of their reinforcement, pre-stressing and post-stressing is very topical. The latter method is very efficient for reinforcement of masonry buildings, which was used by B. Petrović on Kamchatka, Russia.

In interventions on concrete structures, authentic or repair materials which call for formation of very narrowly specialized teams are used very often. Lately strengthening of reinforced concrete element sections with externally bonded fiber reinforced-polymer (FRP) composite materials is very popular, and in which the bond of additional elements and the substrate is important [43]. Recently, the same path of application of NSM method and pre-stressing FRP reinforcement in order to strengthen concrete structures is topical in our country. Recent guidelines given by American Concrete Institute, International federation for concrete (FIB) and Concrete Society Council (UK) can be used for dealing with the design of such sections as there are no national or international standards.

Over the period **2011 – 2014** the Ministry financed the following projects related to structural engineering:

- *Development and application of scientific methods in designing and building of highly economical structural system by implementing new technologies (M. Nestorović);*
- *Research of potential for application of waste and recycled materials in concrete composites, with the evaluation of their influence on the environment, for the purpose of promotion of sustainable civil engineering in Serbia* (V. Radonjanin);
- *Development and improvement of methods for analysis of structure and soil interaction on the basis of theoretical and experimental research* (V. Prolović);
- *Development and application of comprehensive approach to design of new structures and assessment of safety of existing structures with the aim of reducing the seismic risk in Serbia* (Đ. Lađinović);
- *Research of the impact of traffic vibrations on structures and people with the goal of sustainable development of cities* (M. Petronijević);
- *Research of status and methods of improvement of engineering structures from the aspect of serviceability, bearing capacity, cost-effectiveness and* maintenance (Z. Mišković).

Topical themes dealing with seismic were present at 15th World conference of earthquake engineering (EE) in Lisbon, Portugal, from 24th to 27th September and those are: Geotechnical EE; Seismic behaviour of engineering structures; Assessment and retrofitting; Lifeline systems; Social and economic aspects of earthquake. In the paper: *Effects of multiple earthquakes on the seismic response of structures – Contemporary civil engineering practice, Novi Sad* (A. Liolios, 2012), it was demonstrated that apart from the action of an isolated earthquake, it is necessary to introduce the multiple earthquakes.

Numerous papers related to the seismic enhancement of the existing structures, mostly by applying FRP elements [27] and [34]. It is the topic of several journals, such as [2]: The overall performance of hollow clay tile infilled RC frames strengthened with carbon fibre/reinforced polymer (CFRP) materials is experimentally investigated in the paper: *Seismic strengthening of infilled reinforced concrete frames with* *composite materials* (S. Ozden, et al.) and others. The mentioned journals considered several other topical issues. Control of dynamic response of structure is the new philosophy of design [7], with the potential that the structure is transformed from the passive status into active subject able to adapt to seismic action. Particularly topical are the problems of interaction structure-foundation-soil [32], and the meetings with such topics are organized [42] and tend to be organized in the future. The papers of soil-foundation interaction with introduction of viscous properties are still topical [22], and classification of damage and its causes as in the papers [16] and [17] which were the result of the work in the technical committee 104 DCC (Damage classification of concrete) of RILEM, where the author of this text worked with B. Zakić 1987-1992. In addition, B. Zakić worked in several other committees.

Improvement of Bridge Management System (BMS) is the subject of many researches such as [11], [13] and [50]. It is attested by the site http.://www.dot.wisconsion.gov (Wisconsin Department of Transportation, WisDOT Bridge Manual, Madison, WI, 2010). Very topical is the application and improvement of orthotropic slabs in large span bridges, [36], and the meeting IDE was dedicated to innovation as an important factor of development, and it was held in Niš [35].

Publication of topic issues is active in the region, too, such as: Analysis of the effects of reduction of stiffness on the seismic resistance of structures [9], paper: *Seismic dampers in engineering structures* (A. Nižić and D. Meštrović) and several papers dealing with the same issue which are published in several last issues of the journal. The forecast model for determination of fire resistance [38] and numerical model for anticipation of structural behaviour in fire [49] are also very topical and will continue to be such.

The journal CBMS published by STMS Serbia is regularly published in Serbian and English. The journal has an international editorial board and it is open for the authors from the region and other countries.

## 7 Conclusion

From the list of doctoral dissertations in the field of structural engineering, it can be stated, that they are, in major part, the result of individual work and enthusiasm of the individuals. From the list and brief analysis of papers published in Bulletin/Journal M&S and presented at the Conventions and Congresses of STMS, and the list of scientific-research projects at the faculties and institutes, it can be concluded that they represent a significant contribution to the structural engineering of Serbia. It is particularly important that these results were realized by the modest finances available to support science in Serbia.

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- Centar za konstrukcije i prednaprezanje

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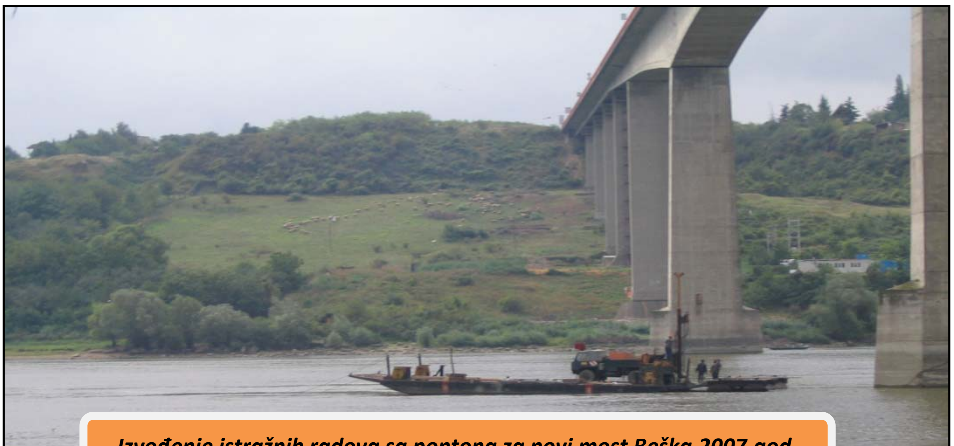
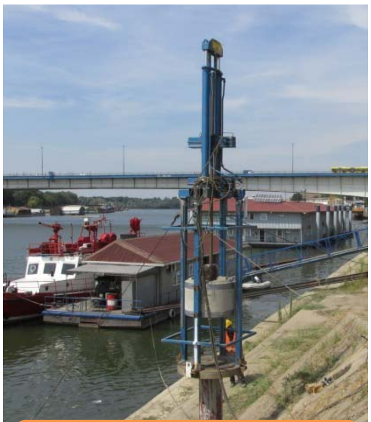


*Izvođenje istražnih radova sa pontona za novi most Beška,2007.god.*

## Geotehnička istraživanja i ispitivanja – in situ

Od terenskih istražnih radova izdvajamo izvođenje istražnih bušotina (IB), standardnih penetracionih opita (SPT), statičkih penetracionih opita (CPT i CPTU), opita dilatometarskom sondom (DMT i SDMT), ispitivanja vodopropustljivosti tla različitim terenskim metodama (VDP), ugradnja pijezometara i dr.

Terenske metode ispitivanja šipova zauzimaju značajno mesto u našoj delatnosti, a na tržištu se izdvajamo kao lideri u toj oblasti u protekloj deceniji.



DLT-dinamičko ispitivanje šipova

## Ispitivanje šipova

**SLT metoda (Static load test)** ispitivanje nosivosti šipova statičkim opterećenjem;

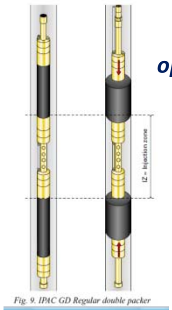
**DLT metoda (Dynamic load test)** ispitivanje nosivosti šipova dinamičkim opterećenjem;

**PDA metoda (Pile driving analysis)** omogućava praćenje i optimizaciju procesa pobijanja prefabrikovanih betonskih i čeličnih šipova u tlo;

**PIT (SIT) metoda (Pile(Sonic) integrity testing)** koristi se za ispitivanje integriteta izvedenih šipova (dužine, prekida, suženja ili proširenja).

CPT/CPTU opiti

Aktivno klizište



*oprema za ispitivanje vodopropusnosti stena pod pritiskom do 10 bar-a metodom LIŽONA*

## Laboratorija za puteve i geotehniku

Laboratorija za puteve i geotehniku akreditovana je kod Akreditacionog tela Srbije – ATS prema SRPS ISO/IEC 17025:2006. U njoj se vrše ispitivanja tla (identifikaciono–klasifikaciona ispitivanja, fizičko–mehanička modelska ispitivanja), kamenog agregata i brašna, bitumena i bitumenskih emulzija, asfaltnih mešavina. U okviru laboratorijskih ispitivanja na terenu vrši se kontrola kvaliteta ugrađenog materijala i izvedenih radova ( prethodna, tekuća, kontrolna ispitivanja i izvođenja opita in situ ).

## Projektovanje puteva i sanacija klizišta

U okviru projektovanja značajno mesto u radu zauzimaju geotehnička istraživanja terena i projekti sanacije klizišta - nestabilnih kosina useka i nasipa puteva i prirodno nestabilnih padina . Značajna su i projekovanja svih vrsta fundiranja specijalnih geotehničkih konstrukcija. Ističe se i iskustvo u oblasti putarstva, na projektovanju novih, rehabilitacija i rekonstrukcija postojećih puteva svih rangova sa pratećim objektima i dimenzionisanjem kolovoznih konstrukcija.

## Nadzor

Naši inženjeri imaju veliko iskustvo u kontroli i proveri kvaliteta izvođenja svih vrsta radova, kontroli građevinske dokumentacije i praćenju radova u skladu sa njom, kao i rešavanju novonastalih situacija tokom izvođenja radova.

# UZ MAPEI SVE JE OK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# PUT INŽENJERING


Put inženjering d.o.o punih 25 godina radi kao specijalizovano preduzeće za izgradnju infrastrukture u niskogradnji i visokogradnji, kao i proizvodnjom kamenog agregata i betona. Preduzeće se bavi i transportom, uslugama građevinske mehanizacije i specijalne opreme.

Za spravljanje betona koristimo drobljeni krečnjački agregat sa našeg kamenoloma, deklarisanih frakcija, kontrolisane vlažnosti. Kompletan proces proizvodnje i kontrole kvaliteta vršimo prema važećim standardima.

Kao generalni izvođač radova, vršimo koordinaciju svih učesnika na projektu, planiranje, praćenje i nabavku materijala, kontrolu kvaliteta izvedenih radova, poštujući zadate vremenske rokove i finansijski okvir investitora.


Obradu armature vršimo brzo, stručno i kvalitetno, sa kompjuterskom preciznošću i dimenzijama po projektu.

Osnovi princip našeg poslovanja zasniva se na individualnom pristupu svakom klijentu i pronalaženje najoptimalnijeg rešenja za njegove transportne i logističke potrebe.

Koristeći inovativne tehnike i kvalitetan građevinski materijal iz sopstvenih resursa, spremni smo da odgovorimo na mnoge zahteve naših klijenata iz oblasti niskogradnje.

Naša kompanija u oblasti visokogradnje primenjuje sistem prefabrikovnih betonskih elemenata koji u odnosu na klasičnu gradnju ima brojne prednosti.

Usluge građevinskom mehanizacijom vršimo tehnički ispravnim mašinama, sa potrebnim sertifikatima kako za rukovaoce građevinskim mašinama tako i za same mašine.


Osnovna prednost prefabrikovane konstrukcije jeste brzina kojom konstrukcija može biti projektovana, proizvedena, transportovana i namontirana.

Prednapregnute šuplje ploče su konstruktivni elementi visokog kvaliteta, proizvedeni u fabrički kontrolisanim uslovima.

Raspolažemo opremom i mašinama za sve zemljane radove, kipere i dampere za rad u teškim terenskim uslovima, automiksere i pumpe za beton, autodizalice, podizne platforme.

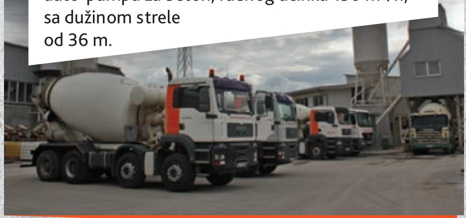
Izvodimo hidrograđevinske radove u izgradnji kanalizacionih mreža za odvođenje atmosferskih, otpadnih i upotrebljenih voda, izvođenjem hidrograđevinskih radova u okviru regulacije rečnih tokova, kao i izvođenjem hidrotehničkih objekata.

Izrađujemo betonske "New Jersey profile" koji se u svetu koriste za preusmeravanje saobraćaja i zaštitu pešaka u toku izgradnje puta, kao i Betonblock sistem betonskih blokova.

Sakupljanje i privremeno skladištenje otpada vršimo našim specijalizovanim vozilima i deponujemo na našu lokaciju sa odgovarajućom dozvolom. Kapacitet mašine je 250 t/h građevinskog neopasnog otpada.

Površinski kop udaljen je 35 km od Niša. Savremene drobilice, postrojenje za separaciju i sejalica efikasno usitnjavaju i razdvajaju kamene agregate po veličinama. Tehnički kapacitet trenutne primarne drobilice je 300 t/h.

Uslugu transporta vršimo automikserima, kapaciteta bubnja od 7 $m^3$ do 10 $m^3$ betonske mase. Za ugradnju betona posedujemo auto-pumpu za beton, radnog učinka 150 $m^3$/h, sa dužinom strele od 36 m.



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## Oplatna tehnika.

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**Panelna oplata za ploče Dokadek 30 – Evolucija u sistemima oplate za ploče**

Dokadek 30 je ručna oplata lake čelične konstrukcije, bez nosača sa plastificiranim ramovima, koji su prekriveni kompozitnim drveno-plastičnim panelom površine do 3 $m^2$.

**Izuzetno brzo, bezbedno i lako postavljanje oplata**

- Mali broj delova sistema i pregledna logistika uz samo dve veličine panela (2,44 x 1,22 m i 2,44 x 0,81 m)
- Dovoljan 2-člani tim za jednostavnu i brzu montažu elemenata sa tla bez merdevina i bez krana
- Sistemski određen položaj i broj podupirača i panela, unapred definisan redosled postupaka
- Prilagođavanje svim osnovama zahvaljujući optimalnom uklapanju sa Dokaflex-om
- Specijalni dizajn sprečava odizanje panela pod uticajem vetra
- Horizontalno premeštanje do 12 $m^2$ Dokadek 30 pomoću DekDrive

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