SLOVAK UNIVERSITY OF TECHNOLOGY

FACULTY OF CIVIL ENGINEERING

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Dissertation Thesis Abstract

DEVELOPMENT OF CONCRETE COMPOSITES BASED ON ALTERNATIVE RAW MATERIALS FOR MASSIVE MONOLITHIC STRUCTURES

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INTRODUCTION

State of the art

The dissertation thesis work is focused on describing the current state-of-art of heavyweight concrete. To be used as biological radiation protection in nuclear facility structures, concrete must be of high density, hence the so-called “heavyweight concrete.” Their attenuation capacity is conditioned by the choice of aggregates, in this case, high bulk density. Each used material in the concrete can influence the final properties of such concrete [1].

As a rule, concrete with a standard bulk density, and thus made of a normal aggregate, is sufficient as protection before the X rays with a wavelength from $1\ 10^{-6}$ till $1\ 10^{-9}$ cm. With decreasing wavelength, in the case of γ-rays (radiation) only $5\ 10^{-11}$ cm, radiation transmittance becomes greater. The concrete must be heavy to reduce the γ radiation by the concrete of an acceptable thickness and, therefore, as low as possible. The thickness of baryte concrete with a density of 3500 kg m^{-3} for gamma-ray attenuation is about 100 mm. In the case of water, it is about 300 mm; in the case of ordinary concrete, about 150 mm and finally, in the case of lead, only 25 mm. In contrast, for the fast neutrons, the thickness of the same baryte concrete for attenuation is about 80 mm; in the case of water, about 100 mm; in the case of ordinary concrete, 110 mm; and in the lead, it is about 90 mm. Considering the use of the concrete with steel gravel, whose bulk density would reach 4300 kg m^{-3}, this concrete attenuation thickness would be reduced by about 20% [2].

Choosing the suitable type of binders is also one of the important issues of such concrete design. For heavyweight concrete binders, it is vital to bind as much water as possible during hydration (even at high temperatures) and thus slow down or stop the progress of fast neutrons from a collision with the hydrogen core. In fact, by selecting suitable binders, the slow neutron absorption and the fast neutron absorption of heavyweight concrete are ensured [3].

It is better to fight global warming using nuclear energy than others (thermal power, wind turbines, hydroelectric power, etc.) [4]. In the case of Wind turbines or Hydro Power Plants, most indigenous plants and animals will experience negative impacts. Thus, the mortality of birds due to wind turbines or fish due to hydropower turbines is increasing [5]. But, of course, just in case of full and accident-free protection. Therefore, all aspects of the nuclear industry must be improved. Thus, the protective concrete must be improved to minimize the environmental impact.

Its primary role is to protect the nuclear reactor from outside influences as a structural material and prevent workers' irradiation from neutron and gamma rays[6]. Therefore, it is necessary to deal with this topic and constantly improve all aspects, from design to production technologies, and long-term features (strength, stability, shielding, etc.) of these constructions [7].

The aims of the work

The main aims of the Dissertation work are:

1. Development of High-Strength Heavyweight Concrete (HSHWC) with the potential attenuation capacities against gamma and neutron radiations.
2. Development of Normal-Strength Heavyweight Concrete (HWC) with the potential attenuation capacities against gamma and neutron radiations.
3. Development of heavyweight concrete like the existing concrete used for shielding purposes.
4. Verify the rheology and physical, thermophysical, and mechanical properties and the attenuation ability of concretes.
5. Summarize the key findings for further development in the field of heavy concrete

To achieve the aims needs to be accomplished the following goals:

1. Selection of Supplementary Cementitious Materials (SCMs) for use as cement re-placement at different substitution levels. SCM will be selected based on knowledge of the current state of the art and on previous work on multi-component cementitious systems that are investigated at the Department of Building Materials and Structures from the USTARCH SAS.
2. Design of the concrete composition will be based on an experimental calculation method and several previous experimental designs for the composition of such concrete.
3. Preparation and curing conditions and their impact on the physical-mechanical properties of the concrete.
4. Realization of attenuation experiment with ^{60}Co emitter in the laboratory of Department of Nuclear Physic of Institute of Physics SAS. Determination of the concrete's linear and mass attenuation coefficient.

The practical significance of the dissertation

The work is focused on verifying the influence of selected parameters of the composition of three heavyweight's concretes on their engineering properties. The contribution of the work lies in the specification of functional heavyweight concrete formulations with added properties for more diverse use in areas where it is necessary to prevent the penetration of nuclear radiation.

The experimental part is divided into thematic units. First, the methodology of heavyweight concrete composition design is described. Subsequently, the work deals with analyzing materials used to produce heavyweight concrete. Then, the results from the physical-mechanical testing of concretes are analyzed separately for each type of heavyweight concrete. Finally, the discussion focuses on describing the possible adaptation of the presented heavyweight concrete recipes given by their resulting properties. Also, individual analyses of the properties of these concretes are compared.

At the end of the work are formulated the contributions of these concretes for practice resulting from the content of the work.

Approbation and publication of research results

Results of the research are presented in three scientific publications included in the Clarivate Analytics WoS database: two published, one accepted in the Journal of Thermal Analysis and Calorimetry (Current Content), and one reported in Proceedings of the conference “Brittle Matrix Composites 12” (2019, Warsaw ADMB).

In addition to those already mentioned, the two scientific publications are included in the Scopus database: one of them was published in the Solid State Phenomena as a proceeding of the conference “International Conference on Building Materials, Products and Technologies” (2019, Brno ADMB) and second in the Materials Science Forum journal ADMB. Furthermore, the results of the dissertation thesis have also been presented and reported at the following six conferences with Proceedings: “Chemistry and Life” (2018, Brno, ADMB), “Betonárske dni” (2018, Bratislava AEDA); Maltoviny (2018, Brno AFC); “JTACC2” (2019, Budapest, AFG) “Kvalita cementu 2021” (2021, Znojmo AFC); “Betón 2021” (2021, Bratislava AFD). Also, the results were regularly presented and discussed at the meetings of Join project V4-Korea in Budapest, Smolenice, and Warsaw, at meeting SK-KR in Soul and Bratislava.

Within the mentioned articles and participations, the work was awarded the V4 Travel Grant 2019 (V4 -Thermoanalytical Conference), and 3rd place in the competition of doctoral students within the AACEE 2021 doctoral conference.

EXPERIMENTAL PART

Characteristics of materials used and their physical properties

The determination of the density of materials was performed using an automatic gas pycnometer Quantachrome Pentapyc 5200e. The specific surface area was measured using a Blaine method and an Autosorb iQ gas sorption analyzer by the BET method. The results are given in [8]. XRF analysis of chemical propagation is provided in [8].

Natural aggregates barite (SABAR, s.r.o., Markušovce, Slovakia) for mixtures HSHWC1, HSHWC3-4, HSHWC6, HWC1-3, and EDU and magnetite (LKAB Minerals, Ltd., Luleå, Sweden) for mixtures HSHWC2-3, HSHWC5-6 and HWC1-3, were used as fillers. Synthetic aggregate cast-Iron crumb (IKB Slévárna Písečná, s.r.o., Písečná, Czech Republic) for EDU was used. The aggregate composition in the individual mixtures is given in [8]. The used aggregate was sieved into individual standardized fractions, and a grain size curve defined their re-mixing with a nominal maximum aggregate grain size of 16 mm, the detailed design of which ensures an ideal distribution of aggregate grains in the concrete. The aggregate grain size distribution curve is depicted in Fig. 1.

A mixture of Portland cement EXTRACEM CEM I 42.5 R (CRH Slovensko, a. S. Rohožník, Slovakia), blast furnace slag -BFS (Kotouč Štramberk, spol. s. r. o., Czech Republic), metakaolin -MK L05 Mefisto (České lupkové závody a.s., Nové Strašecí, Czech Republic), LL (Calmit, spol. s.r.o., Bratislava, Slovensko) and silica fume -SF (Oravské ferozliatinárske závody, a. s., Istebné, Slovakia), were used as components of binder.

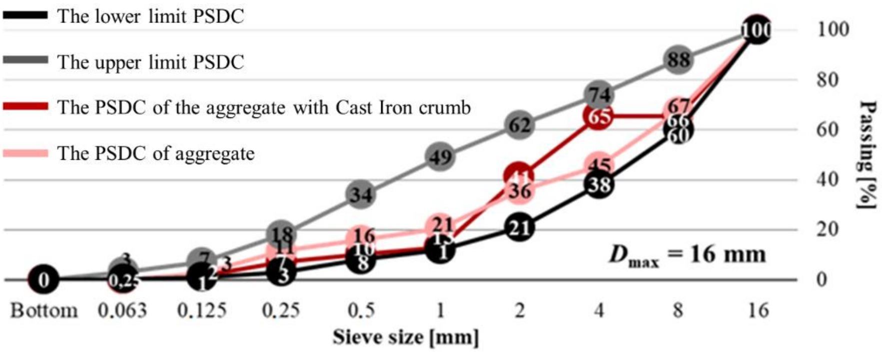

Fig. 1 Particle size distribution curve (PSDC).

Plasticizer Stachement 2000/2025/3000 (ST2000/2025/3000) (SP; density 1065 kg m^{-3}, dry matter content 30 ± 1.5% and pH value 5.0-8.0) (STACHEMA Bratislava, a.s., Slovakia) was mixed into the mixing water in the amount 0.6 kg per 100 kg of cement for HSHWC and HWC concrete mixtures. Retarding additive based on the Ralentol recipe (STACHEMA Bratislava, a.s., Slovak Republic) was added to the EDU concrete mix.

Tab. 1 Determination of density and specific surface area of used materials.

Material	Density ρ [kg m^{-3}]	Specific surface [cm^2 g^{-1}]
BA	4050 - 4150	230 - 310
LD	6800-7800	-
MAG	4850 - 5190	180 - 230
CEM	3143	4341
BFS	2904	4275
SF	2318	15000
MK	2627	13120
LL	2700	8160
SP	1065	-
Voda	1000	-

Tab. 2 Composition of used aggregate for individual concrete mixtures [wt.%].

Mixture	HSHWC1	HSHWC2	HSHWC3	HSHWC4	HSHWC5	HSHWC6	HWC1	HWC2	HWC3	EDU
BA	100	100	-	-	65	65	65	65	65	65
MD	-	-	100	100	35	35	35	35	35	-
LD	-	-	-	-	-	-	-	-	-	35

Tab. 3 Composition of binder (in wt.%) for individual heavy concrete mixtures.

Mixture	w_{PC}/%	w_{BFS}/%	w_{LL}/%	w_{MK}/%	w_{SF}/%	w/c
HSHWC1,3,5	100	-	-	-	-	0.31
HSHWC2,4,6	75	15	-	5	5	0.31
HWC1	75	15	5	5	-	0.53
HWC2	65	20	10	5	-	0.53
HWC3	55	25	15	5	-	0.53
EDU	100	-	-	-	-	0.44

Used methodology

Enormous amounts of generated heat in the structure, especially in the case of massive structures, can cause thermal expansion due to the temperature gradient between the core and surface of the concrete. In the case of the nuclear reactor, accumulated heat in the structure can increase the temperature to 400 °C. In this case, and after the long-term explosion, the C-S-H phase, CH, or other hydration products are decomposed [9]. Thus, calorimetric measurements of pure cement paste, and paste comprised of OPC and SCMs were conducted on TAM AIR 8-Channel calorimeter to detect generated heat at different stages of hydration. Ordinary, the measurement starts a few seconds after adding the water in ($w/b = 0.5$) and will stop after seven days [10].

The consistency of fresh concrete is highly affected by used materials, mainly by chemical admixtures. They could modify the rheology of hardened concrete but also the rheology and consistency of fresh concrete [11], [12]. In the case of heavyweight concrete, it is impossible to avoid adjusting the composition of the concrete with these materials to meet the required standard properties. The biggest issue in the case of heavy concretes is the heavy aggregate grains through the eventually light matrix, dense consistency in the case of high-strength heavyweight. For this reason, the normative test "Slump test BS EN 12350-2:2019: Testing fresh concrete" was made for standard concrete. Subsequently, was **visually verified the segregation** of mixtures **by cutting hardened samples**.

The bulk density of the used aggregate mediates a significant part of the density of concrete, as the aggregate content in concrete is about 70 to 80% [11], [13]. Thus, the importance of density monitoring during the manufacturing process is necessary. The following methods were used to monitor bulk density in the following order. **First, bulk density of aggregate** was detected by the most usual method of Measuring cylinder. **Next, the bulk density of fresh concrete** was measured according to BS EN 12350-6, where density determination is detected by the weight of empty and filled mold. **Finally, the bulk density of hardened concrete** was determined by the exact measured dimensions (cubes with dimensions 150 x 150 x 150 mm and prisms 100 x 100 x 400 mm) using a digital sliding scale and the weight of the samples. The measurements were done at half the length of the sides of the samples and the ends of the sides of the samples, 1 cm from the edge. Finally, weight was determined by the laboratory weight scale, the accuracy of which is 0.01g.

Verification of **durability** consisted of a set of measurements divided into three main measurement sets, namely **the detection of physical**

properties (shrinkage, bulk density, weight, and dynamic modulus of elasticity) depending on the shrinkage of concrete, **the thermal properties measurement** (thermal conductivity coefficient, thermal resistance, thermal diffusivity, and volume heat capacity) realized in two different curing conditions (during the shrinkage and after the standard curing conditions) and **the mechanical properties measurement** (compressive strength on cubes and prisms, flexural strength, static modulus of elasticity and dynamic modulus of elasticity) which were followed till 28 days or 180 days.

The linear and mass attenuation coefficient represents the attenuation properties of concrete for each sample to demonstrate the effectivity of selected materials, especially for shielding purposes [14]. To calculate the attenuation coefficient, the intensity of emitter I_0 and residual intensity I after sample transition must be known [15]. These intensities were obtained in cooperation with the Department of Nuclear Physics of the Institute of Physics SAS by attenuation experiment with a ^{60}Co emitter. The basis of the experiment is depicted in the scheme in Fig. 2. Subsequently, the attenuation coefficient for the radiation shield's real sample thickness can be calculated using the Beer-Lambert law [16].

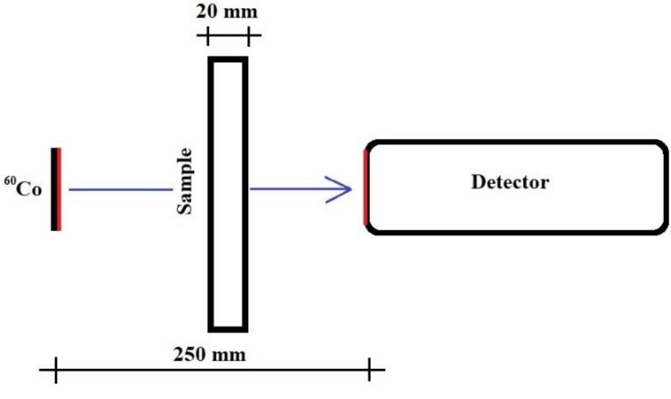

Fig. 2 Schematic arrangement of the gamma ray course from emitter to detector

RESULTS AND DISCUSSION

Chemical analysis, Neutron activation and Gamma activation analysis of the individual used materials.

The chemical analysis of the used materials created a complete analysis of the elements and oxides of the future concrete. NAA and PGAA did the complete isotope analysis with isotopes that are potential threats after irradiation, thus isotopes with a long half-life period (Co, Eu, Ce, Sc, Cr). According to this NAA and PGAA analysis, used materials have appropriate activation properties for the shielding concrete.

Calorimetric measurement and hydration heat

In Tab. 4 are presented all binder mixture compositions. Since the calorimetric measurement is provided with uniform w/c = 0.5, also EDU sample is signed as C1. Subsequently, from the results depicted in Fig. 3, it can be stated that OPC (C1) evolves the most considerable hydration heat during the monitored hydration time of 50 h.

Tab. 4 Composition of binder mixtures used in this research.

Mixture	w_{PC}/%	w_{BFS}/%	w_{LL}/%	w_{MK}/%	w_{SF}/%	w/c
C1- HSHWC1,3,5	100	-	-	-	-	0.31
C2- HSHWC2,4,6	75	15	-	5	5	0.31
C3- HWC1	75	15	5	5	-	0.53
C4- HWC2	65	20	10	5	-	0.53
C5- HWC3	55	25	15	5	-	0.53
C1- EDU	100	-	-	-	-	0.44

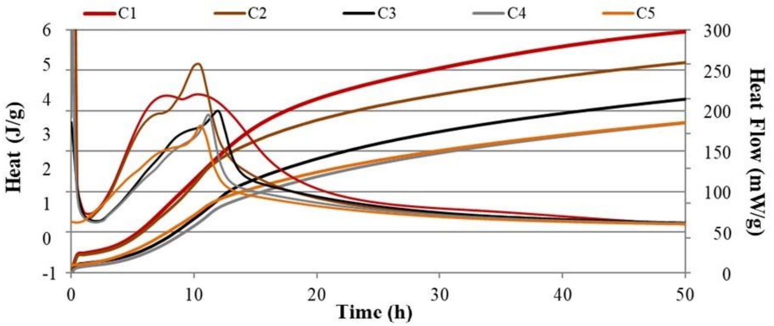

Fig. 3 Calorimetric measurement of all samples of binder used in this research.

There is an assumption that with a lower w/c ratio it will be more so. On the contrary, there can be detected a significant difference between C2 and C3 where is only one difference, thus the exchange of SF by FGL, more so, it is just 5% replacement. Thus, can be stated that FGL significantly decreased the amount of created heat evolution during the monitored time of hydration 50 h. At least can be stated that there is not any significant difference between C3 and C4 thus the 55% SCMs replacement no longer significantly affects the development of heat in the cement paste.

Physical properties

The physical properties of all concrete mixtures are quite similar. Bulk density changes accordingly to the bulk density of used aggregate. Weight loss due to shrinkage ranges between 0.5% and 1.5% and increasing according to increasing of used w/c ratio (highest 2% for HWC3 with w/c = 0.53, lowest 0.45% for HSHWC6 with w/c = 0.31 and 0.55% for EDU with w/c = 0.44).

Surprisingly, the EDU sample presents a significant shrinkage of 1.25‰ compared to developed samples. The lowest shrinkage value reached sample HWC2 0.21‰ and the highest, except EDU, sample HSHWC1 0.47‰. Thus, it can be

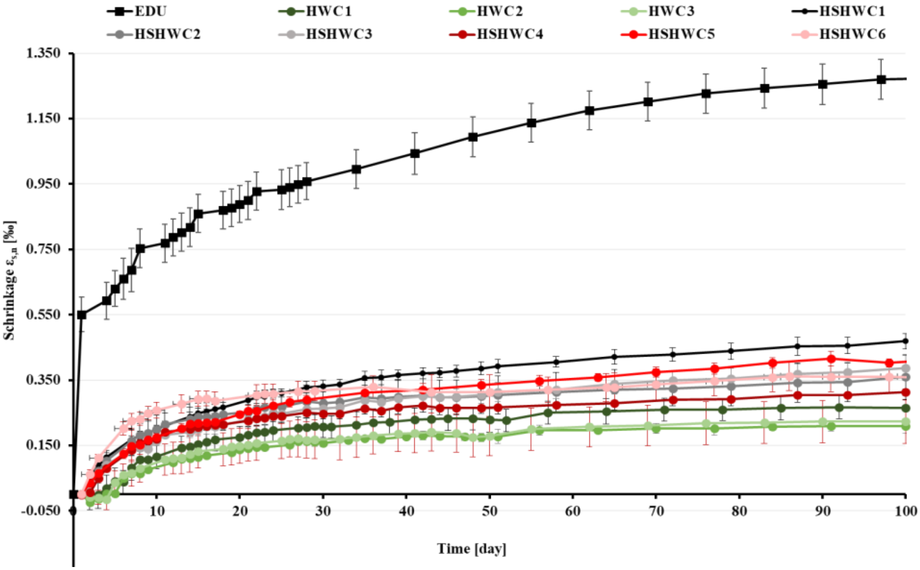

Fig. 4 Shrinkage of all samples in 100 days.

stated that both developed concrete designs, HSHWC and HWC, are appropriated for use in construction. In the case of EDU, due to its already used, there is an assumption for higher concrete shrinkage in the concrete structure.

Thermal properties

The thermal properties were studied according to the type and composition of the aggregate since the aggregate constitutes almost 80% of the composition of the concrete. For this purpose, two types of aggregates (baryte and magnetite), one synthetic aggregate (Cast Iron Crumb), and the combination of baryte and synthetic aggregate in a ratio of 65/35 were considered. Due to economic and environmental aspects, baryte was preferred as a dominant natural aggregate. However, based on the results listed in the chapters 6.3.3 and 7.3.3, synthetic aggregate significantly increased the thermal conductivity coefficient λ and volume heat capacity $c\rho$, thus decreasing the thermal resistance R and thermal diffusivity a.

In accordance with the thermal properties, results can be stated that the use of syn-thetic aggregate is appropriate.

Mechanical properties

According to the mechanical properties results, all the concrete samples meet the designed parameters, especially the strength class.

From the results shown in Tab 9.2 and listed in Chapters 5.3.2, 6.3.2, and 7.3.2, magnetite aggregate MagnaDense improved the mechanical properties (as presented by the supplier LKAB Minerals).

Subsequently, it can be stated that also baryte aggregate is shown as a highly suitable aggregate with good mechanical properties when used in concrete.

Although Cast Iron Crumb in the EDU concrete ensured good mechanical properties, there is still a relevant issue on shrinkage.

The results show the increasing trend in mechanical properties in favor of BPC(HSHWC). On the other hand, in the case of HWC, mechanical properties show a slightly decreasing trend in values with increasing SCMs substitution.

Tab.5 28-day mechanical properties of HSHWC, HWC, and EDU concrete.

Type of concrete	Bulk density	Compressive strength in cube	Compressive strength in prism	Flexural strength	Static modulus of elasticity
Unit	kg m^{-3}	MPa	MPa	MPa	GPa
HSHWC1	3300	81.10	76.13	4.14	35.06
HSHWC2	3080	71.34	70.75	4.84	35.39
HSHWC3	3720	79.73	73.63	6.11	37.10
HSHWC4	3700	93.63	87.60	10.18	40.85
HSHWC5	3320	76.33	70.88	5.16	34.95
HSHWC6	3290	83.97	75.25	5.34	36.02
HWC1	3430	49.78	47.75	7.68	30.93
HWC2	3490	49.23	47.25	7.08	31.80
HWC3	3500	46.15	39.88	7.49	32.68
EDU	3960	81.48	59.00	4.70	38.50

Attenuation properties

The results of the described experimental investigation of linear and mass attenuation coefficients can be concluded as follows.

- Linear and mass attenuation coefficients are not corresponding with each other results since the results of the linear attenuation coefficient correspond to the measured intensities.
- Mass attenuation coefficient reflects the aggregate distribution efficiency and quality along with the amount of the hydration products of manufactured concrete mixture, thus, the effectivity of mass.
- Limestone cement replacement in HWC significantly increased μ of HWC on the contrary to the H. Süleyman Gökçe’s research [18]. A low amount of SF admixture (5%) does not significantly increase the μ. There is potential for 15% replacement [19].

- Cast Iron crumb in EDU (where the baryte aggregate and Cast-Iron crumb were used as an aggregate) significantly increased the linear attenuation coefficient compared with HSHWC1 and 4, where just baryte aggregate was used.
- Magnetite aggregate MagnaDense proved the assumptions declared by the supplier for increasing μ of heavyweight concrete.
- HWC samples have demonstrated the relevance of an optimized composition design. From the results of the linear attenuation coefficient as well as the mass attenuation coefficient, it can be stated that the results for HWC are consistent, and the higher amount of cement substitution for SCMs decreases μ and μ/ρ just negligible.
- Comparing HSHWC (HSHWC3 and 6) and HWC (HWC1) concrete designs, where the same aggregate was used, and BPC, where SF was replaced by FGL, with different water to cement (w/c) ratios (HSHWC 0.31, HWC 0.53); it can be stated that the limestone positively affected the μ and μ/ρ. Subsequently, it can be stated that a higher w/c ratio positively affected the coherence between μ and μ/ρ, thus affecting the mass attenuation.
- According to the presented results, all developed concretes are suitable for γ-radiation shielding purposes. However, there is still an appropriate question about attenuation properties for neutron radiation.

CONCLUSION

The main aims of the Dissertation work were to develop High-Strength Heavyweight concrete (HSHWC) and Normal-Strength Heavyweight concrete (HWC) with the potential attenuation capacities against gamma and neutron radiations and compare them to real HWC design used in the NPP. According to the aims, two heavyweight concretes were developed: HSHWC and HWC. The EDU concrete was made according to the real concrete design due to the Dukovany NPP construction. For the Mixtures was developed the unique PSDC of aggregate with the maximal grain size *Dmax* = 16 and (Fig. 1). The concrete composition was designed according to the Numerical-Empirical method of concrete design conception for both concretes HSHWC and HWC except EDU.

- HSHWC consists of 6 mixtures, where the baryte and magnetite were used as fillers (separately and as a mix of baryte and magnetite in the 65/35 ratio). Two binders were used: OPC (CEM I 42.5R) and BPC consisting of 75% CEM I 42.5R, 15% GGBFS, 5% MK, and 5% SF. BPC was considered based on previous research by E. Kuzielová [11] and M.T. Palou [20] made in the Institute of Construction and Architecture SAS. Stachement 2000 was used as a chemical admixture. A low water-cement ratio w/c = 0.31 was used to ensure high strength. Concrete belongs to the minimal strength class C 55/67 according to STN EN 206-1; thus, one can state that it is a high-strength concrete.
- In mixtures HSHWC3 and 4, MagnaDense is an aggregate with the highest bulk density, the lowest shrinkage, and the highest attenuation range. Therefore, in the case of HSHWC, it has been proved that this concrete should retain standard heavyweight concrete's attenuation properties in parallel with a reduced structure's thickness.

HWC consists of 3 mixtures, where the mix of baryte and magnetite aggregate in the 65/35 ratio was used. They differ in the used BPC, which was optimized from HSHWC BPC. In HWC1, the BPC consists of 75% CEM I 42.5R, 15% GGBFS, 5% MK, and 5% FGL. In HWC2, the BPC consists of 65% CEM I 42.5R, 20% of GGBFS, 5% of MK, and 10% of FGL, and in HWC3, the BPC consists of 55% CEM I 42.5R, 25% of GGBFS, 5% of MK and 15% of FGL. Stachement 2025 was used as a chemical admixture and the water-cement ratio was w/c = 0.53. Concrete has shown relatively high strength despite the high w/c ratio used. It belongs to the strength class C 35/45 according to STN EN 206-1. The bulk density has been preserved despite the higher w/c ratio and the higher cement replacement level with SCMs. The attenuation coefficient was not significantly affected by the higher cement replacement level with SCMs. Therefore, it can be stated that also in the massive monolithic structures, production can be applied an ecological approach with no significant negative consequences.

EDU concrete, where used aggregate consists of the baryte aggregate and synthetic aggregate (Cast Iron Crumb) in the ratio 65/35, OPC (CEM I 42.5R) was used as a binder. Like in the original design with the water-cement ratio w/c= 0.44, the chemical admixture Ralentol and retarder were used. Concrete belongs to the strength class C 60/75 according to STN EN 206-1. Thus, in concrete already used, it can be stated that the durability and rheology of the structure are significantly affected by the selection of used materials.

Moreover, concrete has used a high vol.% of cast iron as an aggregate. This may cause the detected enormous shrinkage despite using a retarding additive. Thus, the use of synthetic aggregates in shielding concretes, therefore, requires future research.

All the goals of the work were met and created the basis for further research as follows:

- Determination of attenuation coefficient for other γ emitters (^{61}Co, ^{152}Eu ^{154}Eu, etc.).
- Determination of coefficient for neutron radiation.
- Development of Ultra-High-Performance Heavyweight concrete UHPHWC, which will be able to maintain the same or higher attenuation properties with the ability to reduce the thickness of the structure significantly.

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SLOVENSKÁ TECHNICKÁ UNIVERZITA V BRATISLAVE

STAVEBNÁ FAKULTA

Ing. JANETTE PODHORSKÁ

Autoreferát dizertačnej práce

VÝVOJ BETÓNOVÝCH KOMPOZITOV NA BÁZE ALTERNATÍVNYCH SUROVÍN PRE MASÍVNE MONOLITICKÉ KONŠTRUKCIE

Na získanie akademického titulu „*Philosophiae doctor“, v skratke „PhD.“*
v študijnom programe: technológia stavieb
v študijnom odbore: stavebníctvo
Forma štúdia: denná

V Bratislave, dňa 29.6.2022

Dizertačná práca bola vypracovaná na Oddelení materiálov a štruktúr, Ústavu stavebníctva a architektúry, Slovenskej akadémie vied v.v.i., Bratislava

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Autoreferát bol rozoslaný dňa: ……………………………………

Obhajoba dizertačnej práce sa bude konať dňa ……………..o ……..…hod. na katedre materiálového inžinierstva a fyziky, Stavebnej fakulty Slovenskej technickej univerzity v Bratislave, Radlinského 11, 810 05 Bratislava.

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Prof. Ing. Stanislav Unčík, PhD.
Dekan Stavebnej fakulty

ÚVOD

Súčasný stav problematiky

Dizertačná práca je zameraná na popis súčasného stavu techniky v oblasti ťažkého betónu. Aby bolo možné použiť ako biologickú radiačnú ochranu v konštrukciách jadrových zariadení, betón musí mať vysokú hustotu a musí zodpovedať bežne nazývaným ťažkým betónom. Ich útlmová schopnosť je podmienená výberom kameniva, v tomto prípade vysokej objemovej hmotnosti. Každý použitý materiál v betóne môže ovplyvniť výsledné vlastnosti takéhoto betónu [1].

Ako ochrana len pred röntgenovým žiarením s vlnovou dĺžkou od 1 10^{-6} do 1 10^{-9} cm spravidla postačuje betón so štandardnou objemovou hmotnosťou, teda z bežného kameniva. S klesajúcou vlnovou dĺžkou, v prípade γ-lúčov, ktorá je len 5 10-11 cm, sa priepustnosť žiarenia zväčšuje. Na zníženie žiarenia γ betónom s prijateľnou hrúbkou, a teda čo možno najnižšou, musí byť betón ťažký. Hrúbka barytového betónu s hustotou 3500 kg m^{-3} pre útlm gama žiarenia je cca 100 mm. V prípade vody je to asi 300 mm; v prípade bežného betónu asi 150 mm a nakoniec v prípade olova len 25 mm. Naproti tomu pre rýchle neutróny je hrúbka rovnakého barytového betónu na zoslabenie asi 80 mm; v prípade vody asi 100 mm; v prípade bežného betónu 110 mm; a vo vedení je to asi 90 mm. Vzhľadom na použitie betónu s oceľovým štrkom, ktorého objemová hmotnosť by dosahovala 4300 kg m^{-3}, by sa táto hrúbka útlmu betónu znížila asi o 20 % [2].

Výber vhodného typu spojív je tiež jednou z dôležitých otázok takéhoto návrhu betónu. Pre ťažké betónové spojivá je životne dôležité naviazať počas hydratácie (aj pri vysokých teplotách) čo najviac vody a tým spomaliť alebo zastaviť postup rýchlych neutrónov z kolízie s vodíkovým jadrom. V skutočnosti je výberom vhodných spojív zabezpečená pomalá absorpcia neutrónov a rýchla absorpcia neutrónov ťažkého betónu [3].

V boji proti globálnemu otepľovaniu je lepšie bojovať s jadrovou energiou v porovnaní s inými (tepelná energia, vodná energia atď.) [4]. V prípade veterných turbín alebo vodných elektrární ohrozuje existenciu väčšiny pôvod-ných druhov živočíchov v mieste elektrárne ci turbíny, takže úmrtnosť vtákov v dôsledku veterných turbín alebo rýb v dôsledku vodných elektrární narastá [5]. Ale samozrejme len v prípade dôkladnej ochrany a bez úrazu. Z tohto dôvodu je potrebné zlepšiť všetky aspekty jadrového priemyslu. Preto je potrebné zlepšiť aj ochranný betón, aby sa minimalizoval dopad na životné prostredie. Jeho primárnou úlohou je chrániť jadrový reaktor pred vonkajšími vplyvmi ako konštrukčný materiál a zabrániť ožiareniu pracovníkov neutrónovým a gama žiarením [6]. Preto je potrebné zaoberať sa touto témou a neustále zdokonaľovať všetky aspekty, od návrhu cez výrobné technológie až po dlhodobé vlastnosti týchto konštrukcií (pevnosť, stabilita, tienenie a pod.) týchto konštrukcií [7].

Ciele práce

Hlavnými cieľmi dizertačnej práce sú:

1. Vývoj vysokopevnostného ťažkého betónu (HSHWC) s potenciálnymi útlmovými kapacitami proti gama a neutrónovému žiareniu.

2. Vývoj normálneho ťažkého betónu (HWC) s potenciálnou schopnosťou útlmu voči gama a neutrónovému žiareniu.

3. Vývoj ťažkého betónu, ako je existujúci ťažký betón používaný na účely tienenia.

4. Overiť reológiu a fyzikálne, tepelno-technické a mechanické vlastnosti betónov a ich útlmovú schopnosť.

5. Zhrnúť kľúčové zistenia pre ďalší rozvoj v oblasti ťažkého betónu

Na dosiahnutie cieľov je potrebné splniť tieto ciele:

1. Výber doplnkových cementových materiálov (SCM). SCM budú vybrané na základe poznatkov súčasného stavu problematiky zmesových cementov a na základe doterajších prác na viaczložkových cementových systémoch, ktoré sú skúmané na Ústave stavebníctva a architektúry, SAV v.v.i.

2. Návrh zloženia betónu bude založený na experimentálno-výpočtovej metóde a na niekoľkých predchádzajúcich experimentálnych návrhoch na zloženie takéhoto betónu.

3. Overiť podmienky prípravy a ošetrovania a ich vplyv na fyzikálno-mechanické vlastnosti betónu.

4. Realizácia experimentu útlmu žiarenia vyrobených betónov so žiaričom ^{60}Co v laboratóriu Oddelenia jadrovej fyziky FÚ SAV v.v.i. Stanovenie koeficientov útlmu betónu.

Praktický význam dizertačnej práce

Práca je zameraná na overenie vplyvu vybraných parametrov zloženia troch ťažkých betónov na ich výsledné vlastnosti. Prínos práce spočíva v špecifikácii funkčných receptúr ťažkých betónov s pridanými vlastnosťami pre rôznorodejšie využitie v oblastiach, kde je potrebné zabrániť prenikaniu jadrového žiarenia. Experimentálna časť je rozdelená do tematických celkov.

Najprv je opísaná metodika návrhu zloženia ťažkého betónu. Následne sa práca zaoberá analýzou materiálov používaných na výrobu ťažkých betónov. Výsledky fyzikálno-mechanického skúšania betónov sú analyzované samostatne pre každý typ ťažkého betónu. Diskusia je zameraná na popísanie možnej úpravy prezentovaných receptúr ťažkého betónu, čo je dané ich výslednými vlastnosťami. Porovnávame aj jednotlivé rozbory vlastností týchto betónov.

V závere práce sú formulované prínosy týchto betónov pre prax vyplývajúce z obsahu práce.

Schvaľovanie a zverejňovanie výsledkov výskumu

Výsledky výskumu sú prezentované v troch vedeckých publikáciách zahrnutých v databáze Clarivate Analytics WoS: dve z nich boli publikované v Journal of Thermal Analysis and Calorimetry AFG a jedna je uvedená v zborníku z konferencie „Brittle Matrix Composites 12“ (2019, Varšava ADMB).

Okrem už spomenutých sú v databáze Scopus zaradené aj dve vedecké publikácie: jedna z nich bola publikovaná v Solid State Phenomena ako zborník z konferencie „International Conference on Building Materials, Products and Technologies“ (2019, Brno ADMB) a druhý v časopise Materials Science Forum ADMB. Výsledky dizertačnej práce boli prezentované a prezentované aj na týchto štyroch konferenciách: „Chemistry and Life“ (2018, Brno, ADMB), „Betonárske dni“ (2018, Bratislava AEDA); Maltoviny (2018, Brno AFC); “JTACC2” (2019, Budapešť, AFG) “Kvalita cementu 2021” (2021, Znojmo AFC); “Betón 2021” (2021, Bratislava AFD). Výsledky boli pravidelne prezentované a diskutované na stretnutiach Join project V4-Korea v Budapešti, Smoleniciach a Varšave, a tiež na stretnutiach SK-KR v Soule a Bratislave.

V rámci spomenutých článkov a účiastí bola práca ocenená V4 Travel Grantom 2019 (V4 -Thermoanalytical Conference), a 3. miestom v súťaži doktorandov v rámci dokroandskej konferencie AACEE 2021.

ZÁVER A VÝZVA NA ĎALŠÍ VÝSKUM

Hlavným cieľom dizertačnej práce bolo vyvinúť vysokopevnostný ťažký betón (HSHWC) a typický ťažký betón (HWC) s potenciálnymi útlmovými schopnosťami proti gama a neutrónovému žiareniu a porovnať ich so skutočným návrhom HWC používaným v JE. Podľa cieľov boli vyvinuté 2 ťažké betóny prvý HSHWC a druhý HWC. Betón EDU bol vyrobený podľa skutočného návrhu betónu použitého z dôvodu výstavby JE Dukovany. Pre Zmesi bola navrhnutá unikátna PSDC kameniva s maximálnou zrnitosťou Dmax = 16. Zloženie betónu bolo navrhnuté podľa numericko-empirickej metódy koncepcie návrhu betónu, pre oba betóny HSHWC a HWC okrem EDU.

HSHWC pozostáva zo 6 zmesí, kde bol ako kamenivo použitý baryt a magnetit (samostatne aj ako zmes barytu a magnetitu v pomere 65/35). Ako spojivo sa použil OPC (CEM I 42,5R) a BPC pozostával zo 75 % CEM I 42,5R, 15 % GGBFS, 5 % MK a 5 % SF. BPC bol navrhnutý na základe predchádzajúceho výskumu realizovaného v Ústave stavebníctva a architektúry SAV E. Kuzielovej [11] a M.T. Paloua [62]. Ako prísada bol použitý Stachement 2000. Na zabezpečenie vysokej pevnosti bol použitý nízky vodný súčiniteľ, w/c = 0,31. Betón patrí do minimálnej pevnostnej triedy C 55/67 podľa STN EN 206-1, možno teda konštatovať, že ide o vysokopevnostný betón. Zmesi HSHWC3 a 4, kde bol použitý MagnaDense ako kamenivo, preukázali najvyššiu objemovú hmotnosť, najnižšie zmrašťovanie a najvyšší rozsah útlmu. Možno teda konštatovať, že v prípade HSHWC sa potvrdil predpoklad, že tento betón by si mal zachovať útlmové vlastnosti typického ťažkého betónu súbežne so zníženou hrúbkou konštrukcie.

HWC pozostáva z 3 zmesí, kde bol použitý mix barytového a magnetitového kameniva v pomere 65/35. Líšia sa použitím BPC, ktorý bol optimalizovaný z HSHWC BPC. V HWC1 pozostáva BPC zo 75 % CEM I 42.5R, 15 % GGBFS, 5 % MK a 5 % FGL, v HWC2 pozostáva BPC zo 65 % CEM I 42.5R, 20 % GGBFS, 5 % MK a 10 % FGL a v HWC3 BPC pozostáva z 55 % CEM I 42.5R, 25 % GGBFS, 5 % MK a 15 % FGL. Ako prísada bol použitý Stachement 2025. Použitý pomer voda-cement bol w/c = 0,53. Betón preukázal relatívne vysokú pevnosť napriek použitému vysokému vodnému súčiniteľu. Patrí do pevnostnej triedy C 35/45 podľa STN EN 206-1. Objemová hmotnosť zostala zachovaná aj napriek vyššiemu w/c pomeru a vyššej náhrady cementu za SCMs. Koeficient útlmu nebol významne ovplyvnený vyššou náhradou cementu za SCMs. Preto možno konštatovať, že aj vo výrobe masívnych monolitických konštrukcií možno uplatniť ekologický prístup bez výraznejších negatívnych dôsledkov.

Betón EDU, kde použité kamenivo pozostáva z barytového kameniva a syntetického kameniva (liatinová drť) v pomere 65/35, bolo použité spojivo OPC (CEM I 42,5R). Rovnako ako v pôvodnom návrhu bola prísada Ralentol, ktorá sa už nevyrába, tak bol použitý regulátor tuhnutia vyrobený na rovnakej báze s obdobnými vlastnosťami. Ako bolo stanovené v pôvodnom návrhu, použitý súčiniteľ voda-cement bol w/c= 0,44. Betón patrí do pevnostnej triedy C 60/75 podľa STN EN 206-1. Keďže betón je už reálne súčasťou konštrukcie, možno konštatovať, že životnosť a reológiu konštrukcie výrazne ovplyvňuje výber použitých materiálov. V betóne sa ako kamenivo používa veľké množstvo liatinovej drte. To môže byť príčinou zisteného enormného zmrašťovania napriek použitiu prísady na reguláciu tuhnutia betónu.

Všetky ciele práce boli splnené a vytvorili základ pre ďalší výskum nasledovne:

- zisťovanie koeficientu útlmu pre ostatné γ žiariče (^{61}Co, ^{152}Eu ^{154}Eu atď.).
- detekcia koeficientu útlmu pre neutrónové žiarenie.
- vývoj Ultra-High-Performance Heavyweight betónu UHPHWC, ktorý bude schopný zachovať rovnaké alebo vyššie útlmové vlastnosti so schopnosťou výrazne znížiť hrúbku konštrukcie.