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Optimization and evaluation of structural and shielding concrete for IFMIF-DONES

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ABSTRACT

The aim of this study was to optimize and evaluate structural and shielding concrete for the IFMIF-DONES building. An ordinary concrete of lime-dolomite aggregate from local sources has been chosen for structural concrete and magnetite aggregate was chosen for heavy-weight radiation shielding. The reference for concrete materials design was the one used in the ITER project. After investigations of raw materials, a group of pre-batches were prepared and technical properties – density of compressive strength, were measured. Finally, two compositions have been elaborated – one for structural concrete of density 2.5 g/cm^3 and the second for radiation shielding concrete of density 3.9 g/cm^3. Then a set of 50 × 50 × 5 cm^3 slabs were prepared and sent to the Nuclear Physics Institute of the CAS in the Czech Republic for shielding mock-up experiments. Also the other technical properties like E-modulus, bending strength etc. have been determined. Additionally, radiation shielding efficiency has been calculated based on atomic composition.

1. Introduction

IFMIF-DONES (International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source) is a single-sited research infrastructure for testing, validation and qualification of the materials to be used in future fusion power plants like DEMO (DEMOnstration Power Plant). The facility will utilize a high-current deuteron accelerator (40 MeV, 125 mA) to strike a high-speed flowing Li curtain (15 m/s), and produces high-energy neutrons (up to 55 MeV) with intense fluxes (maximum 10^{15} n/cm^2/s) through stripping reactions. The neutrons will irradiate material samples placed in the test module behind the target, performing complementary nuclear experiments. It will be shielded by steel and concrete structures. References for the material compositions to be used in neutronics and activation calculations within the Power Plant Physics and Technology (PPPT) programme, addressing predominantly the needs of DEMO and the IFMIF-DONES neutron source facility have been specified [1]. Among them, ITER ordinary concrete (OC) of 2.3 g/cm^3 and ITER heavy concrete (HC) of 3.6 g/cm^3 are presented. Their chemical (atomic) composition [2] and density [3] refer to ITER documentation. Primarily, concrete designed in this paper has been assumed to be used as Removable Biological Shielding Blocks (RBSB) blocks inside of the Test Cell and the biological shield of the Test Cell itself but it can be used in any structure of IFMIF-DONES, such as the Complementary Experimental Hall R160 (Fig. 1) and a future DEMO facility depending on the neutron shielding efficiency requirements.

2. Materials and methods

The composition of reference prescribed ITER OC acc to NF EN 206–1, C40/50, XC3/XFI, CEM I 52.5 PM ES VZ, D_{max} 22.4, 210 ± 30

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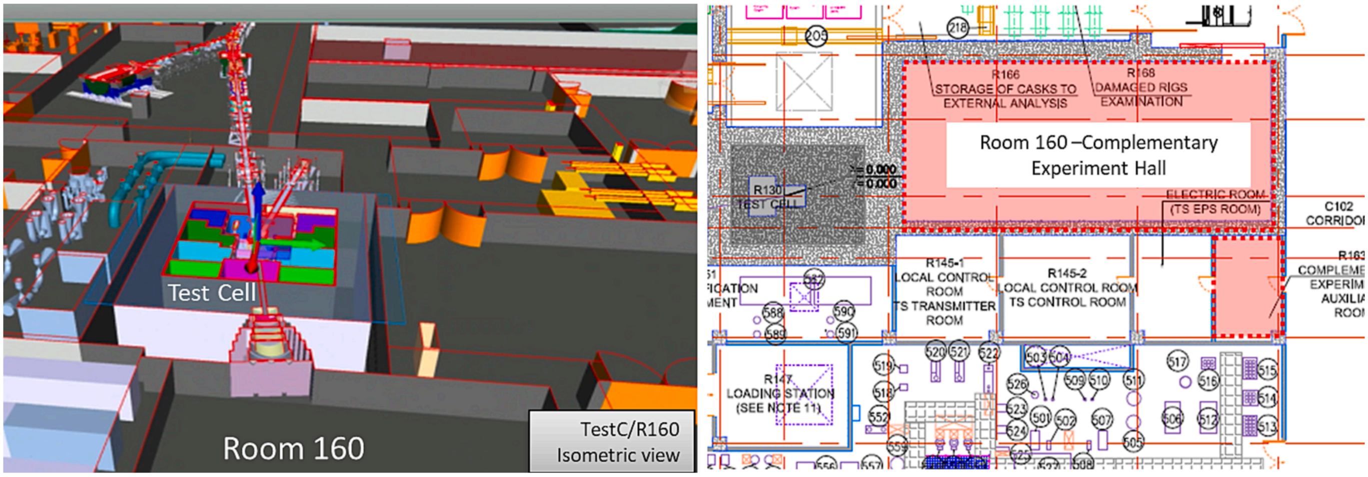

Fig. 1. Location of IFMIF-DONES Test Cell and Complementary Experimental Hall (R160).

Table 1
OC composition for ITER reference concrete and DONES investigated concrete.

OC - ITER reference	[kg/m^3]	OC - DONES investigated	[kg/m^3]
Total aggregate	1745	**Total aggregate**	2000
0/4 semi-crushed limestone sand	900	0/4 dolomite limestone	900
4/16 rolled natural gravel	350	4/8 dolomite limestone	200
11.2/22.4 rolled natural gravel	445	6/12 dolomite limestone	800
Limestone fillers	50	11/22 dolomite limestone	100
CEM I 52.5 N PM ES	240	CEM III/B 42.5 N-LH/SR	360
GGBS	100		
Superplasticizer (Acrylic)	3.12	Superplasticizer (Polycarboxylate)	2.88
Water	190	Water	158.4

mm Cl 0.2 and investigated OC optimized in this research are presented in Table 1. Due to the low accessibility of Portland cement (type CEM I) and possible application in massive structures - requiring low heat generation during hydration of cement - Blast furnace cement (type CEM III) containing 20–34 % clinker and 66–80 % Ground Granulated Blast-furnace Slag (GGBS) has been used. Moreover, the use of a new-generation polycarboxylate superplasticizer allowed for a decrease of water added. As a result, keeping the cement content 360 kg/m^3, the water/binder ratio (w/b) decreased significantly to 0.44 that is in accordance with requirements from Annex F in EN 206 [4] for not only XC3/XF1 but also for the most harmful exposure class XA3 (highly aggressive chemical environment).

For heavy concrete (HC) following the ITER reference the magnetite aggregate has been used as well. Cement and superplasticizer types and contents as well as w/b ratio were the same as in the OC DONES investigated concrete. The magnetite granulometry optimization with fractions 0/2, 0/8 and 0/20 allowed for an increase in total aggregate content up to 3571 kg/m^3 which resulted in much higher density than the reference ITER HC. In order to eliminate the segregation possibility, the starch based viscosity modifying admixture has been used.

After investigations of raw materials, a group of batches were prepared (EN 12390-1) and a group of technical properties – density (EN 12390-7), compressive (EN 12390-3), flexural, (EN 12390-5) and tensile splitting strength (EN 12390-6) were measured [5]. Additionally, a set of 50 × 50 × 5 cm^3 slabs have been prepared and sent to the Nuclear Physics Institute of the Czech Academy of Sciences (NPI CAS) in the Czech Republic for shielding mock-up experiments (Fig. 2). At the NPI CAS, the cyclotron-driven neutron source based on p + Be reaction was used for fast neutron irradiations of concrete mock-ups at U-120 M facility. Using 35 MeV protons the fast neutron generator produces a so-called white energy spectrum with spectral flux intensities up to 7.25 × 10^{10} n/cm^{-2}s^{-1} and 2 × 10^{9} n/cm^{-2}s^{-1} with an accuracy of 12 % for positions 15 mm and 156 mm, respectively [6,7].

3. Neutron shielding efficiency theory and calculation

Neutron shielding is generally a two-step process that does not depend on microstructure [8]. First neutrons of energy over 1 MeV (fast neutrons) are slowed down to less than 0.025 eV (thermal neutrons) and then are absorbed. Following the conservation of momentum, if a neutron hits a large nucleus, it will lose a small part of its energy. But if it collides with a nucleus whose mass is close to the mass of a neutron, the energy loss will be large. That is why the best moderators are light elements in concrete like hydrogen which is present in the chemically

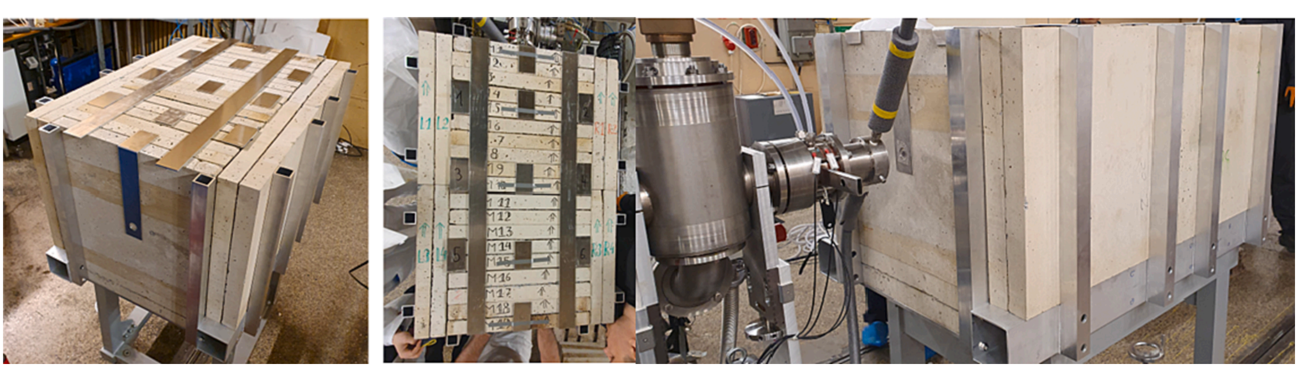

Fig. 2. Shielding mock-up experiments at NPI CAS.

bound water [9] and oxygen which is from aggregate and cement used to make concrete. The other elements contributed by aggregate have relatively smaller effectiveness but due to big total mass can create an important share in total neutron attenuation efficiency. As it was mentioned the second step of neutron shielding is to absorb thermal neutrons. It is independent from the atomic number of the target nuclei or any other simple relation. The best absorbers are neither the light elements (moderators) nor the heavy atoms which are efficient in gamma radiation shielding. The best neutron absorbers in concrete are chlorine (Cl) and iron (Fe). Unfortunately, Cl as a component of reinforced concrete is not recommended and is limited in concrete as it can induce the corrosion of the reinforcing steel. Iron (Fe) is not ideal either, as thermal neutron absorption in iron results in the emission of high-energy secondary gamma radiation and can cause some activation of the concrete as well. For this reason, it is beneficial to use other elements such as gadolinium (Gd), cadmium (Cd), boron (B). Analysis regarding activation of Fe and B in concrete has noted that while concrete containing Fe is more activated in the first years, it becomes less active in comparison to concrete containing B after 10 years of cooling already [10].

The neutron shielding efficiencies of compounds have been compared based on an equivalent absorption cross-section called a *fast neutron effective removal cross-section*, Σ_R [11,12]. It is a linear attenuation coefficient given in cm^{-1} and is defined as a probability that a fast energy neutron undergoes a collision, which removes it from the group of uncollided neutrons. The concept of this phenomenon is based on the presence of hydrogen as it is the main moderator that dominates the attenuation of neutrons. Calculation of *fast neutron effective removal cross-sections* is by analogy to the calculation of mass attenuation coefficients of gamma-rays according to the equation (1):

$$\Sigma_R = \sum_i W_i \cdot (\Sigma_R/\rho)_i \tag{1}$$

where: W_i – partial density of ith constituent, Σ_R/ρ – fast neutron mass removal coefficient of ith constituent

The *fast neutron mass removal cross-section* of constituents is related to the microscopic nuclear properties and varies smoothly with the atomic weight. The value can be calculated using empirical equations or measured. For most elements and some compounds, experimental and theoretical values of the fast neutron mass removal cross-sections have been published [13–15].

Additionally, in order to estimate the neutron shielding efficiency of concrete in a more detailed way, a method based on macroscopic cross-sections for a different interaction has been used [16]. In this method, instead of fast neutron attenuation cross-sections, a database of neutron scattering lengths and cross-sections that includes the thermal neutron microscopic cross-section as well is used [17]. Thus the *macroscopic neutron scattering cross-section* or the *macroscopic thermal neutron absorption cross-section* and finally their sum named the *total macroscopic neutron cross-section* have been calculated using equation (2):

$$\Sigma_j = \sum_i W_i \cdot (\Sigma_j/\rho)_i \tag{2}$$

where: W_i – partial density of ith constituent, Σ_j/ρ – neutron mass attenuation coefficient of ith constituent for a specific interaction (j)

4. Results and discussion

4.1. Technical properties of concrete

An interesting finding was that, despite the heavyweight characteristics of magnetite aggregate, in terms of workability the heavy concrete presented more fluid consistency and less segregation, in comparison with the ordinary one. It has been noticed particularly during the slump test (Fig. 3) that was replicated during the casting of the specimens. It was probably due to the use of viscosity modifying admixture mentioned before. The results regarding density, compressive and flexural strength for ordinary concrete (OC) and heavy concrete (HC) at 28, 40 and 90 days respectively, are presented in Table 2.

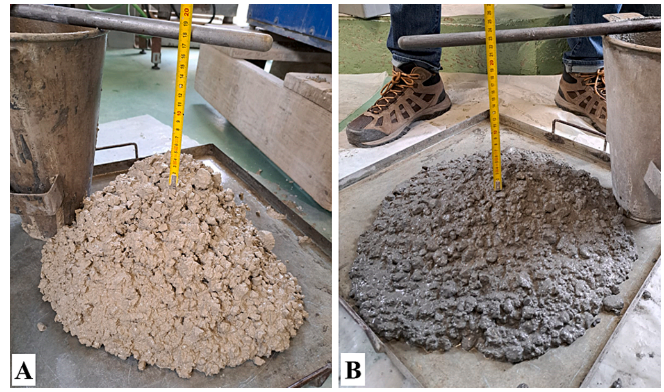

Fig. 3. Slump test (A) OC; (B) HC.

Table 2
Density, compressive and flexural strength.

Concrete	Age [days]	Density [g/cm^3]	Compressive Strength [MPa]	Flexural Strength [MPa]
OC	28	2.511	76.40	10.74
	90	2.507	79.34	11.60
HC	40	3.918	79.00	9.09
	90	3.938	79.94	8.76

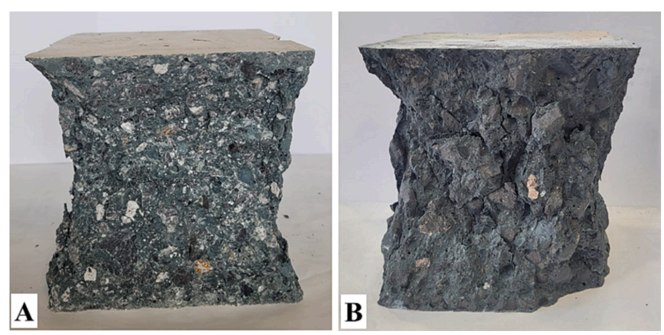

Fig. 4. Typical compressive strength test failure mode (A) OC; (B) HC.

Table 3
Tensile splitting strength and elastic modulus.

Concrete	Tensile splitting strength [MPa]	E-module [GPa]
OC	3.85	57.47
HC	4.34	54.72

Both density and compressive strength are considered critical parameters to study the properties of heavyweight concrete. In accordance with ITER concrete reference values, considering an average compressive strength after 90 days (about 60 MPa), bot OC and HC surpasses the range by 25 % (reaching almost 80 MPa) as can be seen in Table 2. Additionally, it is worth noting that despite the difference obtained for the density and flexural results, the compressive strength is relatively analogous, increasing with curing time. A striking observation was that all specimens exhibited a typical failure mode after the compressive test (Fig. 4).

Table 3 includes the splitting tensile strength and the corresponding

Table 4
Weight fraction of DONES investigated OC and HC.

Element	H	C	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Fe
OC	0.0033	0.1031	0.4958	0.0000	0.0989	0.0075	0.0199	0.0000	0.0107	0.0002	0.0006	0.2421	0.0005	0.0174
HC	0.0020	0.0000	0.2803	0.0018	0.0028	0.0070	0.0259	0.0045	0.0013	0.0001	0.0017	0.0474	0.0003	0.6248

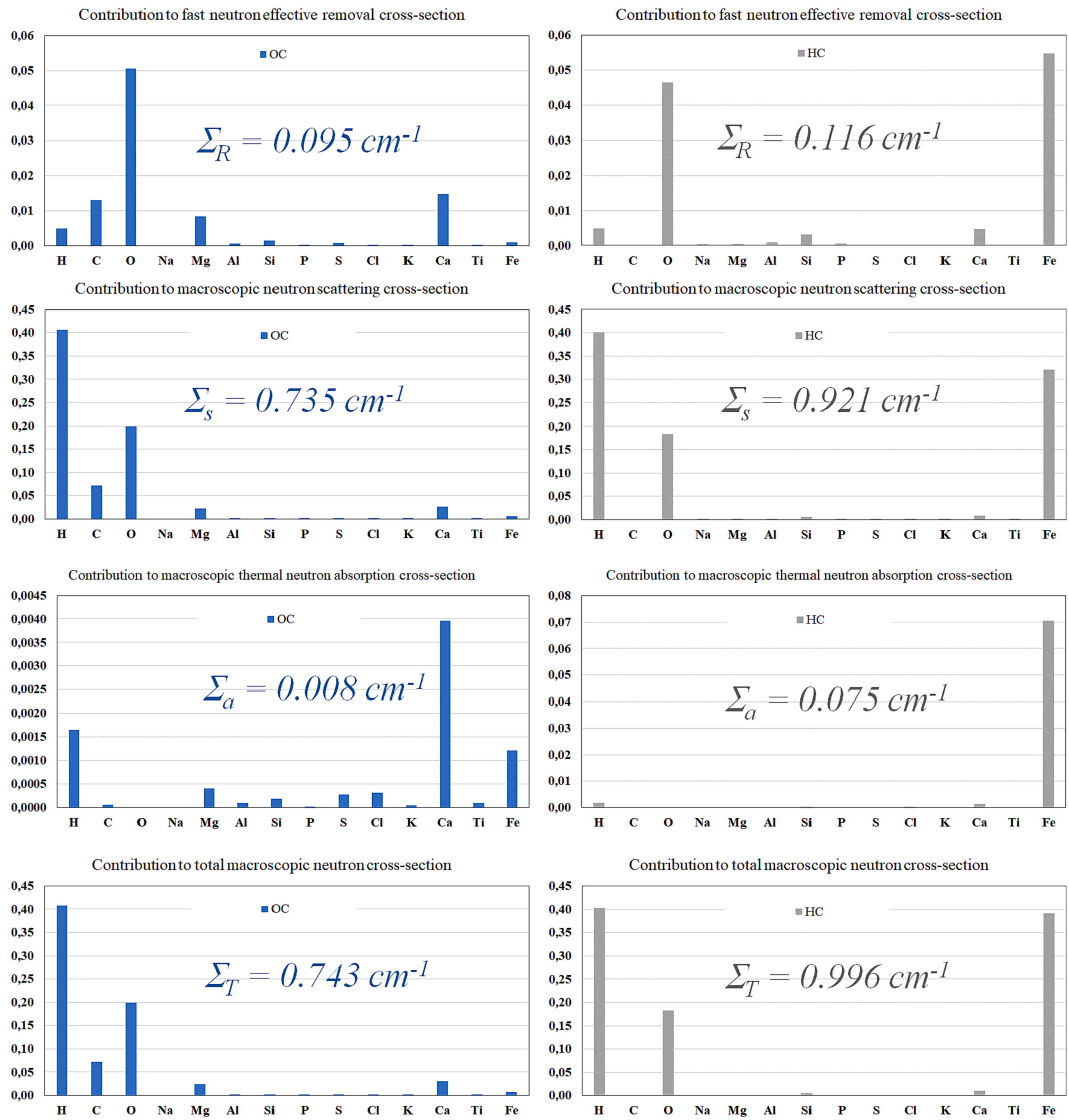

Fig. 5. The contribution of each element in concrete and values of neutron shielding efficiency parameters.

modulus of elasticity for each type of concrete, where the most remarkable fact is the higher tensile strength and lower E-modulus for the HC, compared to the OC.

4.2. *Neutron shielding efficiency of concrete*

The key issue for shielding efficiency evaluation is atomic composition determination. For concrete it was assumed that water in only 20 %

Table 5
Neutron shielding efficiency for ITER reference concrete and DONES investigated concrete.

Concrete	Symbol	OC ITER	OC DONES	HC ITER	HC DONES
fast neutron effective removal cross-section	Σ_R	0.086	0.095	0.105	0.116
macroscopic neutron scattering cross-section	Σ_s	0.718	0.735	0.842	0.921
macroscopic thermal neutron absorption cross-section	Σ_a	0.015	0.008	0.064	0.075
total macroscopic neutron cross-section	Σ_T	0.733	0.743	0.906	0.996

of the cement mass is chemically bound water during cement hydration [4]. Later, weight fractions (Table 4) for specific elements of the concrete and the partial densities from oxide composition of the constituents (cement, aggregate) were calculated. Cement oxide composition was obtained from X-Ray Fluorescence (XRF) analysis. Dolomite aggregate was 87 % pure dolomite with 10 % of calcite and 3 % of iron sulfide. Magnetite aggregate contained more that 90 % of Fe_3O_4 with minor content of Silica, Calcium and Aluminum oxides. The contribution of each element in concrete and values of fast neutron effective removal cross-section - Σ_R, macroscopic neutron scattering cross-section - Σ_s, macroscopic thermal neutron absorption cross-section - Σ_a and total macroscopic neutron cross-section - Σ_T are presented in Fig. 5.

OC is worse in neutron shielding efficiency than HC from every point of view. For HC it has been obtained higher values of fast neutron effective cross-section by 22 %, neutron scattering cross-section by 25 %, thermal neutron absorption cross-section by 838 % and total macroscopic neutron attenuation cross-section by 34 %. Comparing the results between ITER reference concretes and DONES investigated concretes (Table 5) it can be observed an increase of shielding efficiency for DONES concretes exept macroscopic thermal neutron absorption cross-section which is higher for ITER OC due to trace amount of boron (B).

5. Conclusions

The focus of the investigation and design was lime-dolomite based Ordinary Concrete (OC) and Magnetite based Heavy Concrete (HC) to be used in the IFMIF-DONES Test Cell structure. Proper selection and optimization procedure of aggregate and other constituents allowed for the preparation of concrete characterized by better properties than the reference ITER concretes. Structural OC of the target density 2.5 g/cm^3 has superior mechanical properties and radiation shielding, HC is superior in both density of 3.9 g/cm^3 and compressive strength of 80 MPa (the same as OC). Moreover, the neutron shielding efficiency of both concretes has been compared and it was proved by calculation that HC is about one-fourth better than OC when a wide energy range or only fast neutrons are considered and more than 8 times better when only thermal neutron absorption is taken into account. Moreover neutron shielding efficiency of DONES investigated concretes has been superior in comparison to ITER reference ones.

CRediT authorship contribution statement

Tomasz Piotrowski: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **María José Martínez-Echevarría Romero:** Data curation, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing – review & editing. **Piotr Prochon:** Conceptualization, Data curation, Investigation, Resources. **Mónica López Alonso:** Project administration, Supervision, Validation, Writing – review & editing. **Rafał Michalczyk:** Formal analysis, Validation, Visualization. **Armando Arvizu-Montes:** Data curation, Investigation, Methodology, Resources, Software, Writing – original draft, Writing – review & editing. **Łukasz Ciupiński:** Conceptualization, Funding acquisition, Supervision. **Santiago Becerril Jarque:** Funding acquisition, Project administration, Resources, Validation, Writing – review & editing. **Kazimierz Józefiak:** Data curation, Methodology, Validation, Writing – review & editing. **Yuefeng Qiu:** Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Martin Ansorge:** Methodology, Resources, Writing – original draft, Writing – review & editing. **Hari Chohan:** Methodology, Resources, Writing – original draft, Writing – review & editing. **Magdalena Wojtkowska:** Data curation, Formal analysis, Investigation, Software, Validation, Visualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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