Research Article

Aleksandra Radziejowska*, Joanna Sagan and Anna Sobotka

Technological and organizational problems in the construction of the radiation shielding concrete and suggestions to solve: A case study

https://doi.org/10.1515/eng-2021-0082
received October 24, 2020; accepted June 15, 2021

Abstract: Protection of buildings against the pernicious radiation types can be achieved by simultaneous structural and shielding parameters. Those shields are mainly made of heavyweight concrete, which causes many serious problems in the areas of technology, supply logistics, financial supply, Occupational Safety & Health Administration, and substitutions of structural and material solutions. This work presents a case study of the construction of the university building with rooms requiring protection against malicious radiations. Apart from that, it presents the problems and solutions that occurred during the construction from the perspective of the works contractor. This study was also expanded to include the analysis of alternatives for construction-materials. The obtained results were used to develop a generalized scheme, which will be helpful in the preparation and implementation of any facilities requiring fixed radiation shields.

Keywords: high density concrete, radiation shielding concrete, construction work, decision support

1 Introduction

Radiation shielding concrete (RSC) is a technical solution aimed at minimizing the risk associated with the impact of ionizing radiation on the human body, and at the same time they are part of the building structure or fill out the construction [1]. RSC must, therefore, meet the health protection requirements of both: persons whose exposure to radiation is continuous (workplace), and in the case of incidental events (affecting the general public) [2]. Moreover, as an element of the building structure, they must meet the conditions of the ultimate limit state and serviceability, requirements for sound and thermal insulation as well as tightness and durability.

The design and construction of RSC requires an interdisciplinary approach – which is in relation to issues in the field of construction as well as nuclear physics and medicine. In objects where ionizing radiation is anticipated, it is also possible to use structural elements as a help for radiation absorption. For this purpose, high-density concretes based on heavyweight aggregates such as rare and expensive minerals like barite and magnetite are used [3]. However, the construction of partitions with the use of high-density aggregate creates many realization problems in the areas of technology, supply logistics, finance, Occupational Safety & Health Administration (OSHA), and substitution of structural and material solutions. Therefore, for such an investment, there is a need to apply the appropriate methodology in the design and technological decisions of the contractor. It is needed especially in the situation of carrying out investments in the "design and build" system or leaving the decision of implementation, including design, to the general contractor.

This article aims to specify the realization problems occurring during the construction of RSC, which were identified by *case studies* method. Presented set of experiences will help construction engineers identify sources of risk for this kind of projects. The performed analysis of decision-making processes (DMP) will organize and improve the scheme of the DMP to find substitutive technological and organizational solutions.

This work contains an introduction to the issue of designing permanent radiation shields. Section 3 presents a case study of the construction of a teaching building with rooms requiring radiological protection.

* **Corresponding author: Aleksandra Radziejowska,** Department of Geomechanics, Civil Engineering and Geotechnics, Faculty of Civil Engineering and Resource Management, AGH University of Science and Technology, Cracow, Poland, e-mail: aradziej@agh.edu.pl
Joanna Sagan, Anna Sobotka: Department of Geomechanics, Civil Engineering and Geotechnics, Faculty of Civil Engineering and Resource Management, AGH University of Science and Technology, Cracow, Poland

During the analysis of the investment project, special attention was paid to the issue of shields, the adopted solution was assessed against the background of alternatives. Based on the observations, the decisions as well as the sources of risks related to the execution of shielding elements have been presented. Section 6 presents general conclusion and work achievements.

2 Preparation issues of radiation shields

The basis for the proper design of the shield is knowledge of the radiation source characteristics, including [4]:
– the energy range of the primary beam (prior to any interaction),
– type of radiation (electromagnetic radiation: X-rays; gamma radiation (γ); and particle radiation: alpha radiation (α), beta radiation (β), and neutron radiation [particles of non-zero rest energy]),
– radiation geometry (beam geometry).

It is also important to determine the exposure of user groups to radiation and to determine the maximum level of radiation dose that a person can take during the year. Operating scenarios are not insignificant as they determine the theoretical dose level, expressed by the residence coefficient.

Shielding is used as part of radiological protection, and the following materials are used in the construction of covers such as concrete mixes [5,6], lead, steel, paraffin, polymers [4,7–11], modified cement pastes [12–14], glass materials [15], and; bricks [16,17]. Each of them has additional specific features in relation to acting as a shield against the harmful effects of a given type of radiation. Heavy shields are suitable for retaining both α and β radiations as well as γ radiation, but they should not be used in direct contact with fast neutrons because, as a result of their collision with a heavy core of the shield, radioactive isotopes are formed [18]. Lightweight materials (e.g., polyethylene and paraffin) are effective against fast neutrons; however, when a neutron hits light hydrogen nuclei, gamma radiation is produced which must be stopped by heavier shielding. Therefore, a multilayer shielding solution is commonly applied [1]. High-density concretes have a significant advantage over other materials because they can meet both structural and protective requirements. It contains a mixture of many heavy and light elements and thus, has good characteristics for neutron and photon attenuation [1,19,20]. Other advantages include high durability with stable shielding installations, availability of required components, low cost, low maintenance, structural integrity, and efficient manufacturing [21].

High-density concretes are those with a density greater than 2,600 kg/m^3. The volumetric weight is shaped by the quantitative and qualitative share of heavy aggregate fraction. Natural heavyweight aggregates used in high-density concrete are primarily barite, as well as hematite, magnetite, serpentine [22], goethite [23], limonite and ilmenite [24–26]. In RSC, the steel slag [23] and boric acid [27] could also be applied.

As the density of concrete increases, its shielding capacity also increases. The content of appropriate elements in the aggregate makes it possible to reduce the thickness of concrete layers while maintaining mechanical properties [2,5,20,28]. High density of concrete mixture, during construction execution, causes some technological difficulties, e.g., high pressure of concrete mixture on the formwork, difficulties in feeding the concrete mixture, and aggregate segregation. As a result, the quality of the structure may be insufficient and it will not provide the assumed technical parameters in terms of bearing capacity, durability, or shielding.

In addition, it should be remembered that it is necessary to properly design and manufacture shields because of the need to maintain the durability of the material in a sufficiently long period of use of this type of premises. Such structures must be designed for a specific period of time and properties (prescription to performance, P2P), which causes many difficulties, especially due to the lack of proven models to predict the quality of concrete after 50 or 100 years of use [6,29].

3 Case study

3.1 Description of the investment

The subject of the research is the construction investment of the Faculty of Physics and Applied Computer Science (FPACS) currently being implemented in the AGH university (2019–2021). The building structure was designed in a slab-beam-column system with a height of four aboveground floors and one underground floor. In the basement, the building outline is enlarged for the multi-parking underground car park and technical rooms. In addition, a dilated connector is being designed between the building under construction and the existing pavilion D-10 (Figure 2). Consultations with future users of the facility indicated the need for a room for storing radioactive waste, which was included in the tender announcement.

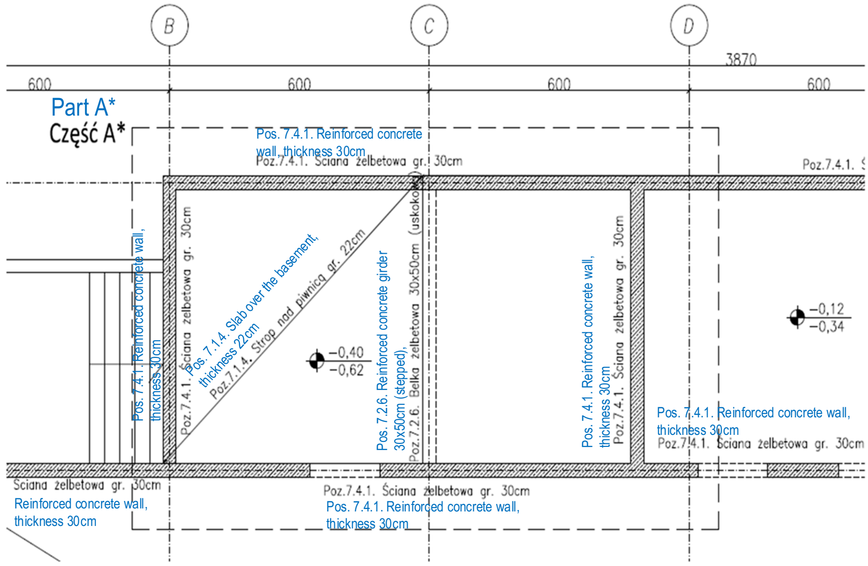


Figure 1: The room marked “Part A*” designed from high-density concrete class C30/37, (documentation AGH university).

In the case of the analyzed project, the shield design was shown on the shutters in the existing building, built in the 1980s, which met the shield requirements for stored radiation sources and operational conditions. No other design solutions were considered. The adopted solution guaranteed that the requirements would be met without having to draw up a radiation protection project. The design adopted the use of fixed guards made of 30 cm thick barite concrete (Figure 1). However, the investor has left the possibility for the contractor to use an alternative material solution.

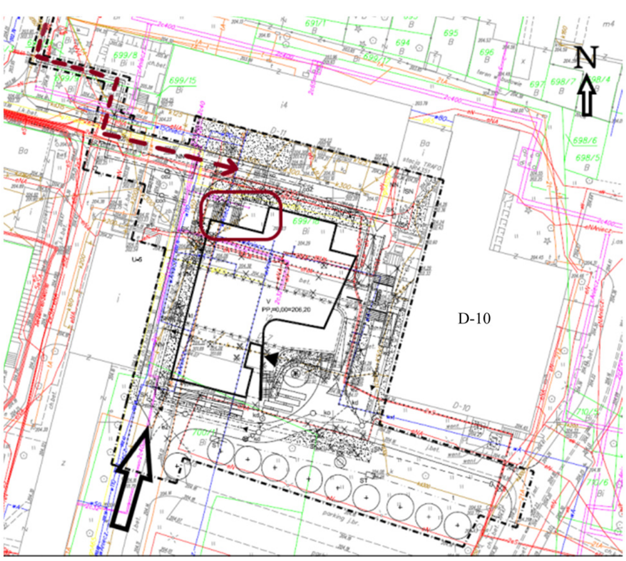


Figure 2: A schematic plan of the area development of the FPACS building with possible access. Source: AGH university procurement documentation.

The technical documentation did not pose any special requirements for the covers and their description was laconic. The material presents assumptions, such as: “locally, barite concrete should be used in a portion of the source/radioactive waste storage areas.” The place of use of RSC was identified in the documentation as “Part A.” Due to the design guidelines, the entire underground structure had to be made in waterproof concrete technology. Finally, in the room intended for the storage of radioactive waste, it was decided to make both walls and slabs of high-density concrete.

3.2 Realization problems

3.2.1 Potential sources of risk

The design and implementation of a permanent RSC have constituted a significant source of risk for the contractor in the building project as well as a potential element of competitive advantage. The primary sources of risk and its negative impacts were related to cost, time, and difficulty in availability of materials including aggregate for concrete and their logistics. However, the contractor has gained experience and increased the image. In addition, there is a possibility of financial benefits in future projects, if the shielding solutions need to be optimized. In the analyzed case, the lack of a detailed radiological protection project that should normally be provided by the investor, made it difficult not only to optimize the construction-material and technological-organizational solutions by potential contractors but also correctly design a feasible solution, including a substitution one.

Due to the uniqueness of the investment and the need to use hard-to-reach aggregates for high-density concrete, a potential contractor, who wants to assess the investment risk and include it in the offer price, should provide an alternative material solution.

The company that won the tender obtained information about radiation sources used in existing AGH university laboratories, which will be stored in the room. In addition, a worst-case scenario against radiation exposure to workers was assumed. The contractor decided to use high-density concrete for all partitions of the room.

3.2.2 High-density concrete logistics planning

During the construction, the contractor did not find a concrete plant in Poland, which would provide heavyweight concrete offer. However, ordering this type of concrete mix is possible abroad, most likely from western or southern neighbors. But due to technological reasons (time of concrete mix transport), this solution was not feasible. The general contractor (GC) surveyed the market by sending inquiries to local concrete plants. In response, the prices were obtained (for mixture with barite or magnetite aggregates) ranging between 4,300 PLN/m^3 and 5,000 PLN/m^3 (PLN – Polish Zloty New). It was decided to take advantage of the cheapest offer. The mix was to be produced in Cracow after importing magnetite and delivered to the construction site. Due to the time needed to deliver aggregate, it was necessary to place an order for magneto-concrete in advance.

An aspect that had to be considered during planning the transport of mix deliveries was its weight. Due to the tonnage restrictions on Polish roads (currently, due to EU law, the maximum axle load for heavy goods vehicles cannot exceed 115 kN; before 2019 it was mostly 80 kN), it was not possible to supply the mixture by filling the entire, most commonly used concrete mixers with a capacity of 10 or 11 m^3. Therefore, a mixture with a density of 3,500 kg/m^3 was delivered to the construction site in concrete mixers only half-filled (5–6 m^3). In the end, about 70 m^3 of magnetite concrete was used in the building.

3.2.3 Preparatory works

In addition to the abovementioned logistic problem, an additional difficulty was the organizing of a suitable device for feeding the mixture [11]. Despite numerous inquiries, the contractor could not find a provider willing to rent the pump. The stated reason was the concern about pump or boom damages, due to the high volumetric weight of the mixture, danger of blocking of the mixture in the pipeline as well as rubbing the rubber hose for feeding the mix. The contractors most often suggested using a concreting bin; however, due to the long transport time of the mix using the basket and its weight (in this case only half the capacity of the basket can be filled), it was purposeful to look for a solution that would provide the shortest time for building the mix. Eventually, a subcontractor was found who agreed to inject the mix at the construction site with a concrete pump.

Another problem was the location of the pump as close as possible to build-in point. As can be seen in Figures 2 and 3, the entrance to the building was from the south, i.e., on the opposite corner of the build-in point. The low reach of the pump arm for feeding the magneto-concrete mix prevented the task from being carried out from this position. Therefore, the delivery and location of the pump from the north side of the investment was planned, with much more difficult access (dashed arrow in Figure 2). To prevent blocking the passage of concrete trucks and pumps on the day of the planned concreting, the capacity of the temporary access road was monitored.

4 Analysis of the implementation of design solutions

The consideration of alternative material solutions was also carried out. It required knowledge of the types of

Figure 3: An image showing the construction site marking the shielding location during the concrete casting. Own source, 25.11.2019.

radiation sources and the conditions of human exposure to radiation. In the course of the work, such information was obtained. Unfortunately, the design conditions prevented changes in the building outline or reduction in the required floor area. Such a scenario could have brought a savings of 250,000 PLN. Another solution considered would be making sandwich partitions from concrete with a density of 2,300 kg/m^3 and a layer of steel or lead. However, this would require significant changes in the project. Modification of the above variant would be the use of a combined partition consisting partly of high-density concrete and partly of layered partition made of plain concrete, where its thickness would be expanded with a free-standing band along the wall to the height of the underground (Figure 4). In the project, a ground floor made of plain concrete could also be considered.

The indicated solution does not change the outline of the building or reduce the usable area. From a technological point of view, it would be problematic to make a contact between two concretes of different densities [30]. And the proposed solution would require the approval of the investor, designer, and radiation protection specialist, i.e., a separate project in this case. The considered solution would reduce the cost of the RSC from 350,000 to 180,000 PLN. The cost difference was estimated by comparing the price per cubic yard of plain concrete (250 PLN/m^3 [Franco]) and heavy concrete (4,300 PLN/m^3 [Franco]).

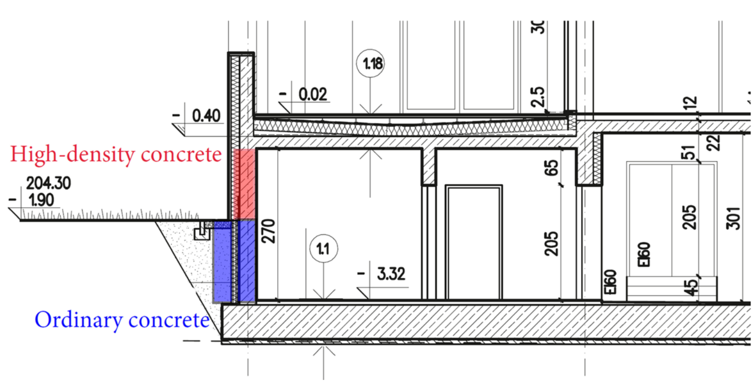
5 Analysis of the decision-making process

Due to the perceived problems of the project requiring the implementation of RSC, a diagram of the decision-making process is presented. The diagram describes the selection of the implementation solution and assessment of design variants from the perspective of the works contractor (Figure 5).

Submission of an offer for the investment (contractor), which includes, in whole or in part, the execution of the concrete fixed shell, should start with the assessment of the initial design. To this end, it is necessary to analyze the design requirements and conduct market research of suppliers of building materials and services.

In the process of market research, it is necessary to find heavy concrete suppliers, or plants that offer the service of producing ready-mixed concrete (including heavy concrete) according to the customer's order and on the basis of delivered semi-products. The analyses should include only those suppliers for which the location conditions do not go beyond the adopted level of technological risk associated with the transport of the concrete mix. It is necessary to assess the conditions of supplying heavy aggregate, which most strongly determines the unit price of concrete for these suppliers. If the concrete plant has an aggregate supply chain and the material price is favorable according to the contractor, an initial design solution should be adopted. However, if the aggregate supplier is the purchaser or the price is not favorable, then a market study should be carried out for heavy aggregate suppliers, taking into account the raw material prices and associated purchase costs. It should also be considered to use a substitution material when searching for the best offer. In addition, in the field of technology and organization related to the implementation of heavy RSC, it is necessary to analyze the contract conditions for reinforced formwork and concrete mix laying services.

Having data on the market of materials and services and knowing the technological and organizational requirements, logistics, costs, and risks associated with the implementation of the design solution and other criteria relevant



where:

1.1 Layers on the basement level:
- epoxy resin floor - 0.5cm
- bottom slab of watertight reinforced concrete with slope for linear drainage
- waterproofing mat
-

1.18 Terrace layers on the west side:
- stone slabs - 5cm
- spacers - min.3cm
- heat-sealable PVC foil
- extruded polystyrene - 20cm
- polystyrene wedges - 0-10 cm
- vapour barrier
- reinforced high-density concrete slab

Figure 4: Variant solution of the RSC.

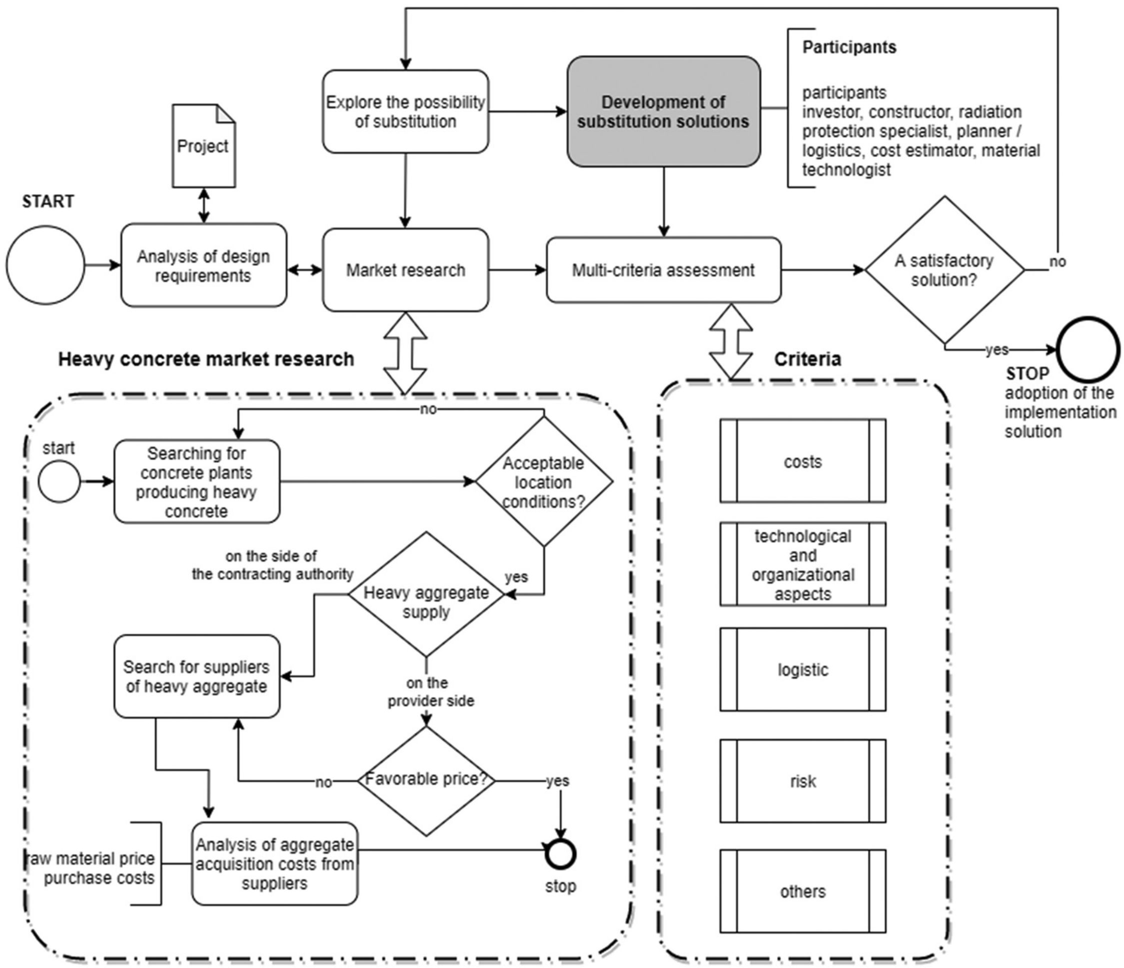


Figure 5: A schematic diagram of the decision-making process in the area of the RSC.

to the contractor in the next step, multi-criteria assessment of variants should be carried out. Then, on this basis, a decision should be made whether to accept the solution for implementation or to look for a substitution solution.

Possible replacement operations should be examined in terms of the market (access to materials and services). It should also be designed taking into account the requirements of the developer, designers, radiation protection specialists, planners, cost estimators, and material technologists. Substitution solutions should also be assessed from the perspective of the criteria adopted in the assessment and on this basis the implementation option should be selected.

Multi-criteria variant assessment of the project, deepened by market research, not only allows for proper mapping of the investment implementation costs but also for the assessment of the project's risk. By the substitution analysis, the contractor in the tender procedure has the option of lowering the price and thus gaining an advantage over the competition.

6 Conclusion

When designing permanent covers and taking into account safety, technical, functional, financial, technological, and organizational criteria, the design decision becomes a complex multi-criteria issue, requiring cooperation of an interdisciplinary team. However, there is a basic problem that the designer (in the general contracting system) does not know the contractor. This leads to the designer only taking into account technological and organizational aspects, without focusing on the individual preferences of the contractor. Making decisions at the design stage also involves a high risk of changes in market prices of materials and the unavailability of raw materials that are running out. This situation results in a higher level of risk for the contractor who will in turn include the risk in the offer price. Defining the requirements for the cover seems to be a more advantageous solution, leaving the question of its implementation entirely to the contractor. In the analyzed example, approximately 4,000 tons of concrete mix was built into the investment, including less than 2% of magnetite. However, due to the significant difference in the price of this material, this small amount accounted for as much as 25% of the cost of the concrete delivered.

The submission of an offer for the construction of an object containing RSC should be preceded by a detailed analysis of the requirements for the shields. An assessment of the design variant should be made, taking into account the current market situation. Research on substitutional solutions can lead to optimization of the project in terms of individual preferences contractor.

Each potential solution should be assessed holistically and multi-criteria – low raw material costs can be associated with e.g., high transport costs or high implementation risk, etc. It is recommended, if possible, to cooperate with contractors to consult the solutions proposed in the project to avoid problems at the implementation stage.

Conflict of interest: Authors state no conflict of interest.

References

[1] Gostkowska B. Ochrona radiologiczna. Wielkości, jednostki i obliczenia. Warsaw: Centralne Laboratorium Ochrony Radiologicznej; 2005.
[2] Pohl E. Technika jądrowa w budownictwie. Warszawa: Arkady; 1967.
[3] Tyagi G, Singhal A, Routroy S, Bhunia D, Lahoti M. Radiation shielding concrete with alternate constituents: an approach to address multiple hazards. J Hazard Mater. 2021;404:124201. Available from: https://www.sciencedirect.com/science/article/pii/S0304389420321919.
[4] Szymańska M, Ciupek K. Promieniowanie jonizujące-ochrona radiologiczna, zastosowanie a odpady promieniotwórcze. Poznań: Fundacja Forum Atomowe; 2011.
[5] Ablewicz Z, Dubrowski WB. Osłony przed promieniowaniem jonizującym: materiały, konstrukcje, wykonywanie. Warsaw: Arkady; 1989.
[6] Brandt AM, Jóźwiak-Niedźwiedzka D, Nowowiejski G, Denis P. Wyniki badania betonu osłonowego z kruszywem magnetytowym. VIII Conference "Dni Betonu – Tradycja i Nowoczesność". Wisla: Dni Betonu; 2014.
[7] Zalegowski K, Piotrowski T, Garbacz A. Influence of polymer modification on the microstructure of shielding concrete. Mater (Basel). 2020;13(3):498.
[8] Szajerski P, Celinska J, Gasiorowski A, Anyszka R, Walendziak R, Lewandowski M. Radiation induced strength enhancement of sulfur polymer concrete composites based on waste and residue fillers. J Clean Prod. 2020;271:122563.
[9] Özdemir T, Güngör A, Akbay IK, Uzun H, Babucçuoglu Y. Nano lead oxide and epdm composite for development of polymer-based radiation shielding material: Gamma irradiation and attenuation tests. Radiat Phys Chem. 2018;144:248–55.
[10] Peymanfar R, Keykavous-Amand S, Abadi MM, Yassi Y. A novel approach toward reducing energy consumption and promoting electromagnetic interference shielding efficiency in the buildings using Brick/polyaniline nanocomposite. Constr Build Mater. 2020;263:120042.
[11] Szajerski P, Bogobowicz A, Gasiorowski A. Cesium retention and release from sulfur polymer concrete matrix under normal and accidental conditions. J Hazard Mater. 2020;381:121180.
[12] Florez R, Colorado HA, Giraldo CHC, Alajo A. Preparation and characterization of Portland cement pastes with Sm_2O_3 microparticle additions for neutron shielding applications. Constr Build Mater. 2018;191:498–506.
[13] Florez R, Colorado HA, Alajo A, Giraldo CHC. The material characterization and gamma attenuation properties of Portland cement-Fe_3O_4 composites for potential dry cask applications. Prog Nucl Energy. 2019;111:65–73.
[14] Ramadan M, Amin MS, Sayed MA. Superior physico-mechanical, fire resistivity, morphological characteristics and gamma radiation shielding of hardened OPC pastes incorporating $ZnFe_2O_4$ spinel nanoparticles. Constr Build Mater. 2020;234:117807.
[15] El-Khayatt AM, Saudy HA. Preparation and characterization of zinc, lanthanum white sand glass for use in nuclear applications. Radiat Phys Chem. 2020;166:108497.
[16] Alorfi HS, Hussein MA, Tijani SA. The use of rocks in lieu of bricks and concrete as radiation shielding barriers at low gamma and nuclear medicine energies. Constr Build Mater. 2020;251:118908.
[17] Mahmoud KA, Sayyed MI, Tashlykov OL. Gamma ray shielding characteristics and exposure buildup factor for some natural rocks using MCNP-5 code. Nucl Eng Technol. 2019;51(7):1835–41.
[18] Sala F. Dozymetria i ochrona przed promieniowaniem jonizującym: aspekty fizyczne, techniczne, prawne i społeczne. Warsaw: Uczelniana Oferta Dydaktyczna PW; 2009.
[19] Al-Buriahi MS, Singh VP. Comparison of shielding properties of various marble concretes using GEANT4 simulation and experimental data. J Aust Ceram Soc. 2020;56(3):1127–33.
[20] Saidani K, Ajam L, Ben, Ouezdou M. Barite powder as sand substitution in concrete: Effect on some mechanical properties. Constr Build Mater. 2015;95:287–95.
[21] Li Z. Advanced concrete technology. Hoboken, New Jersey: John Wiley & Sons; 2011.
[22] Kansouh WA. Radiation distribution through serpentine concrete using local materials and its application as a reactor biological shield. Ann Nucl Energy. 2012;47:258–63.
[23] Abdel-Rahman M, El-Samrah MG, Kany A. Study characteristics of new concrete mixes and their mechanical, physical, and gamma radiation attenuation features. Z für Anorg und Allg Chem. 2017;644(2):92–9.
[24] Esen Y, Doğan ZM. Investigation of usability of limonite aggregate in heavy-weight concrete production. Prog Nucl Energy. 2018;105:185–93.
[25] Topçu İB. Properties of heavyweight concrete produced with barite. Cem Concr Res. 2003;33(6):815–22. Available from: https://www.sciencedirect.com/science/article/pii/S0008884602010633.

[26] Ouda AS. Development of high-performance heavy density concrete using different aggregates for gamma-ray shielding. Prog Nucl Energy. 2015;79:48–55. Available from: https://www.sciencedirect.com/science/article/pii/S0149197014002960.

[27] Zayed AM, Masoud MA, Shahien MG, Gökçe HS, Sakr K, Kansouh WA, et al. Physical, mechanical, and radiation attenuation properties of serpentine concrete containing boric acid. Constr Build Mater. 2021;272:121641.

[28] Brandt AM. Beton jako materiał osłon przed promieniowaniem jądrowym – przegląd. Cem Wapno Bet. 2013;R.18/80(2):115–32.

[29] Dybel P, Walach D, Ostrowski K. The top-bar effect in specimens with a single casting point at one edge in high-performance self-compacting concrete. J Adv Concr Technol. 2018;16:282–92.

[30] Wałach D. Impact of delays during concreting of reinforced high-performance concrete beams. Proc Eng. 2016;161:356–61. Available from: doi: 10.1016/j.proeng.2016.08.574.