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COMPUTATIONAL INVESTIGATION OF GAMMA SHIELDING BEHAVIOR OF CEMENT-BASALT COMPOSITE FOR NUCLEAR ENERGY APPLICATIONS

Bachelor's thesis

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1. Introduction

The purpose of this bachelor thesis is to calculate the viability of using basalt as reinforcement in concrete for nuclear energy applications and to determine whether the addition of basalt fiber in concrete will help improve the overall quality of concrete in terms on strength and durability in nuclear facilities. For this purpose, the pros and cons of using basalt fibers as additional reinforcement considering the changes in the concrete properties and cost for using basalt instead of other fibers are investigated and discussed.

Upon Fukushima accident, where a natural disaster developed to become a nuclear disaster, we saw that strength and radioactivity protection are the two main aspects of reinforced concrete nuclear facilities. One of the main problems of concrete used in nuclear energy applications is the cracking, which leads to moisture penetration which in turn results in gradual degradation. This means that the reinforcing elements will slowly start to disintegrate due to structural deformations caused by cracks, and environment changes in concrete will lead to changes in the chemical structure and inhibit a component or components from maintaining its or their performance requirements. This occurrence can lessen the radiation shielding properties severely. This is the reason cracking is a serious and one of the main problems of structural disintegration and degradation in nuclear power plants (Naus, Oland, Ellingwood, 1996).

If the reinforcing elements are water sensitive such as metals, then oxidation occurs. Even though steel fiber can start off as good reinforcement material, chemical penetrations and moisture absorption in concrete can oxidize the metal and as a result the metal will be corroded away resulting in a severe loss of design strength. (Naus, 2007).

Fibers are proven to be good elements to balance and lessen the ratio of cracking in concrete but using corrosive tendent fibers in concrete will result in a shorter lifespan. This is one of the reasons that the research on current radiation shielding elements is focused on developing and using non-corrosive alternative materials for usage in nuclear facilities with reinforced concrete structure.

It is crucial for the constructing materials to demonstrate radiation shielding properties in nuclear energy applications such as nuclear power plants, nuclear waste repositories, research facilities as well as accelerators, neutron generators and medical facilities (Gulik, Tkaczyk, 2014).

2. Materials

2.1 Concrete and its applications in nuclear energy

Concrete is a composite material consisting of cement, water and aggregates. Steel re-bars are generally added in the concrete as reinforcement, and in some cases fibers can also be used to lessen the occurrence of cracking. For nuclear facilities the durability of concrete is at priority when choosing the type of cement, aggregates and reinforcement. The concrete that is in use today including nuclear power plants is mainly obtained from Portland cement. Portland cement is obtained by mixing crushed limestone, clay, sand and iron ore, heating it to 1400-1600 °C and adding small amount of gypsum to regulate setting and facilitate placement. From this method we get Portland cement that is primarily composed of tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrit. There are also some alternative cementing agents like fly ash or silica fume that change the chemical composition and properties (Naus, 2007).

Water to cement ratio is an important characteristic of the concrete, mainly affecting the elasticity. A high W/C ratio means low strength and high permeability, whereas low W/C ratio means low permeability and high strength. However, cracking is also an important to factor to consider when deciding on the W/C ratio. Concrete is a self-healing material as long as water exists within the mixture, therefore W/C should be carefully calculated, especially for large scale concrete elements (MacGregor, 1997). The water content in the mixture plays a role in making concrete workable. The workability of concrete is determined by 4 characteristics:

1. Fluidity
2. Consistency
3. Compactability
4. No segregation.

Segregation is the separation of coarse and fine aggregates and sometimes even reinforcement; segregation is also the separation of water and solids in concrete. If the concrete mixture has too much water it compromises the hardening of the concrete, if there is too little water the concrete becomes unworkable (MacGregor, 1997).

There are multiple tests that can be performed on site to test the workability of concrete. One way to test the consistency of concrete is a test called the cone test where truncated cone is filled with concrete and positioned on a surface opening side down. Then the cone is lifted slowly and the difference of the height of truncated cone and the height of concrete pile describes the consistency of the concrete. Concrete is workable if the difference between the height of truncated cone and the pile of concrete is 10-210 mm. For different applications the consistency has different values so the workability scale is divided into four classes (Rudus).

Aggregates used in concrete can be divided to three categories respectively to the mass of aggregates:

1. Lightweight,
2. Normal-weight,
3. Heavyweight.

In the lightweight subcategory there are pumice, scoria, perlite, vermiculite, and diatomite. Normal-weight aggregates are limestone and natural sand. Main heavyweight aggregate is barite but also magnetites, limonites and ilmenites are commonly used. In nuclear structures, normal and heavyweight aggregates may be used to improve concrete properties (Naus, 2007).

Some aggregates in concrete are added to change the properties of concrete such as barite and some are added to reduce the costs. Common aggregates can be listed as limestone, granite, sandstone, quartz and basalt. Clay is not a suitable aggregate material. The maximum allowable aggregate size is 31.5 mm while the minimum being 0.25 mm (ACI 318M-02, 2002) (Naus, 2007).

Steel is the most commonly used reinforcement for concrete because steel and concrete work well together, which means that steel binds with concrete. Any segregation in this bond will cause severe damage to the concrete which in turn will result in severe loss of compressive, tensile and shear strength. For this reason, the workability of the concrete is a very important characteristic. This means the perfect combination of coarse and fine aggregates and W/C ratio, where all the voids are filled, resulting in a compactible concrete with no segregation (Arya, 1993) (MacGregor 1997).

There are multiple reinforcement options to reduce the ratio of possible cracks such as carbon fiber, metal fiber, glass fiber, polymer fiber and basalt fiber. These fibers are added to be bonded with concrete making it easier to distribute the loads evenly throughout the concrete element making cracks less likely to occur.

The engineering point of view before starting any project is estimating the desired mechanical properties, cost and durability of each and every structural component. The durability is important because the operating life of any building, except for certain cases, is by standards established to be approximately 50 years (Eurocode 2). This operating life solely depends on the durability of the building materials. The mechanical properties mentioned above depend on three types of stress:

- The tensile loading, also called stress,
- Compressive loading, also called strain,
- And shear loading (MacGregor, 1997).

Concrete for different applications has different requirements. The design strength of is one of the main prerequisites when using concrete in nuclear energy and waste disposal facilities, where the requirement is usually heavyweight concrete. Concrete used in nuclear facilities can be divided into two different parts considering with the operational properties of the specific part of the building. For facilities near reactor and the reactor structure and core there is a strong need for radiation shielding and concrete has to be durable for increased heat. In buildings and structures further away from the reactor there is generally no need for radiation shielding but strength and durability still remain as necessities. The shielding is achievable by adding heavy aggregates to concrete mixture, but this combination must result in minimal voids among cement, aggregates and reinforcement (Naus, Oland, Ellingwood, 1996).

As mentioned above, one of the main problems with concrete is cracking. These are the reasons why cracks occur in reinforced concrete:

1) Before hardening of concrete, cracks are caused by:
    a. Early frost damage
    b. Plastic shrinkage
    c. Plastic settlement
    d. Formwork movement
    e. Sub-grade movement

2) After hardening cracks are caused by:
    a. Physical causes:
        i. Shrinkable aggregates
        ii. Drying shrinkage
        iii. Crazing
    b. Chemical causes:
        i. Corrosion of reinforcement
        ii. Alkali-aggregate reaction
        iii. Cement carbonation
    c. Thermal causes:
        i. Freeze-thaw cycles
        ii. External seasonal temperatures
        iii. Early thermal contraction
    d. Structural causes:
        i. Accidental overloading
        ii. Creep
        iii. Design loads

If cracking occurs at the early stages of concrete formation and setting, then there is suitable amount of water in the concrete and unreacted cement particles, the material can self-heal and still obtain desired strength. If the conditions are unpropitious this process will not take place but the concrete starts to attract unwanted elements through sorption, adsorption and capillary action through the cracks. In addition to water, different salts gain access into the concrete from the surrounding environment which can lead to chemical degradation within the concrete. As concrete has low tensile strength and ductility, cracking cannot be totally eliminated but can be limited (Naus, 2007) (Naus, Oland, Ellingwood, 1996) (MacGregor 1997).

One of main reason for cracking is the shift in loads the concrete designed to carry. For this reason, it is difficult to totally eliminate cracking. The secondary reason for cracking involves aggregates. Larger aggregates weaken the structure and causes temperature changes inside the concrete. The expansion of concrete is not negligible. If the reinforcement does not have similar expansion coefficient, the reaction of concrete and the reinforcement to expansion will be different and this will result in additional stress. This can also affect the bond between concrete and reinforcement which may cause a horizontal or vertical slip between the reinforcement and concrete in case of re-bars (Ólafsson, Þórhallsson, 2009) (Naus, Oland, Ellingwood, 1996).

The width of a crack affects the speed of corrosion but not the way it spreads. When corrosion damages the steel re-bars in concrete, it can cause additional cracking, delamination or spalling. The bond between concrete and reinforcement weakens and the tensile strength reduces. Corrosion also becomes another main problem in concrete due to the wide-spread use of metal bars in concrete (Naus, 2007).

At elevated temperatures concrete starts to degenerate. Different sources mention different temperatures needed for the drop in strength to occur. There are conflicting statements that 700 °C or 800 °C for a short period of time is not damaging enough but 700 °C is considered the temperature at which concrete starts to degenerate at an elevated speed. The largest reduction comes around 749 °C with 27% and second is 700 °C with 17%. This is due to changes in the composition of concrete. Above 600 °C dehydration of calcium-silicate-hydrate occurs which causes the main loss of strength. When heated onwards between 600 °C and 900 °C limestone begins to decarbonize. Above 1200 °C components of concrete start to melt and above 1300 °C concrete exists in form of melt (Naus, 2007).

There are other reasons that may influence the concrete to lose or change its designed properties. In Table 1, there are shown multiple problematic materials that can cause durability problems and deterioration of concrete (MacGregor 1997) (Bowles 1988).

Harmful Materials	Effect
Organic impurities	deteriorations
Coal and lignite	durability problems
Clay	workability, durability
Materials $\rho < 2,4$ kg/dm^3	durability problems
Alkali reactive aggregates	expansion and cracking
$CaSO_4$, Na_2SO_4, $MgSO_4$	durability problems

Table 1 - Hazards and damage they cause to concrete.

2.1.1 Durability and longevity of concrete

As emphasized in the previous section, the main aspects of evaluating concrete suitability are durability and longevity. According to the research and evaluations in United States, the average operational lifespan of a nuclear plant is primarily around 40 years with a secondary lengthened lifespan of additional 20 years and a final need of an approximate 50 years of decommissioning. (Naus, Oland, Ellingwood, 1996). The aging of concrete is associated with changes in creep, modulus, compressive and tensile strengths (Rashid, James, Dunham, 2010). The changes within years divide into three:

- Material dependent changes due to time
- Changes due to the environment
- Changes due to radiation

The durability issue can be influenced by different factors as can be seen on Figure 1. The main aspects of the quality of concrete are the materials used in mix, the structural design, the curing process and workmanship. The last two determine the transport options for water in the structures. When water is transported through the pores into the concrete, degradation starts. These lead to concrete structure weakening until some parts fail to perform.

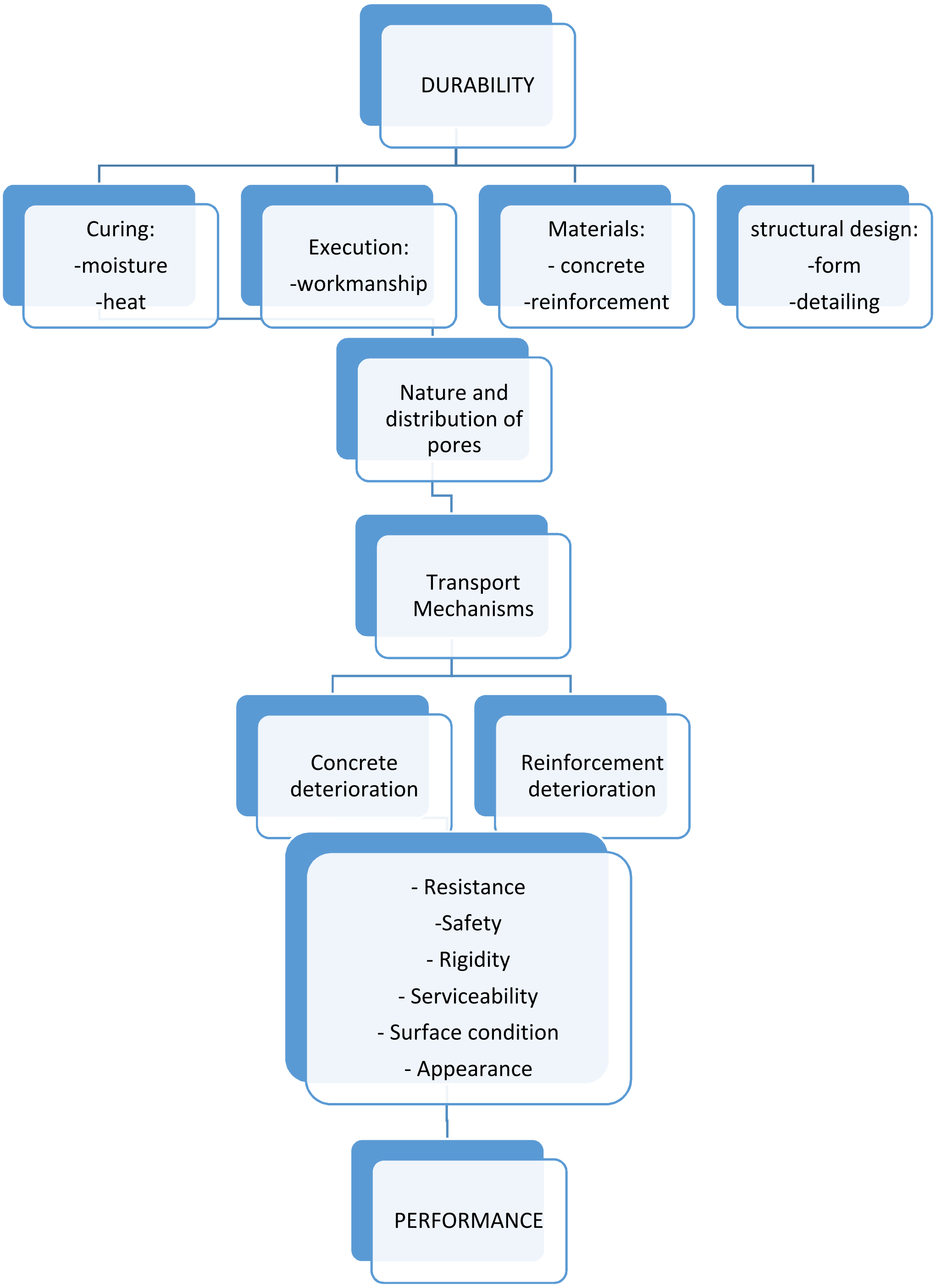

Figure 1 - Factors determining durability

2.2 Products from basalt as reinforcement materials

Reinforcements for concrete have to be considered for the following aspects:

- Will they be distributed homogeneously in the concrete,
- Will they react to environmental factors,
- Will they react to radiation?

The reinforcement distribution in concrete is describable by specific gravity. If the specific gravity is lower than concrete, the material will rise, and the concentration will be higher on top of concrete and lower on the bottom. On contrary, if the specific gravity is higher than concrete, the additional material will sink, and concentration will accumulate on the bottom. For this reason, we would need a material that has more or less similar specific gravity to concrete. This way the distribution will tend to be homogeneous (Sim, Park, Moon, 2005) (Ólafsson, Þórhallsson, 2009).

As concrete is an alkaline environment, reinforcement should stay chemically inert. In laboratory tests basalt and glass fiber degraded in 1M alkali solution losing strength about 50% at 7 days and more than 80% at 28 days (Sim, Park, Moon, 2005). This is a statement that requires additional research and testing as it poses a big problem.

A recent article by V. Gulik and A. Biland (2012) states that there are uranium deposits that contain mainly basalt in the earth's crust in Ukraine. From these deposits, it is observed that basalt does not change in physical or chemical way when exposed to radiation (Gulik, Biland, 2012).

The technology of roving production from basalt originates from Soviet scientists in the 1960/70's, who were interested in the possibility of obtaining roving from basalt by melting and pulling long strands (Gulik, Biland, 2012). Manufacturing basalt fibers is done by melting basalt rock to 1580 °C. The rock is then pushed through small nozzles to produce continuous fiber. The basalt is taken from carefully chosen specific quarries. There is no need to add other materials for achieving basalt roving (Ólafsson, Þórhallsson, 2009).

Figure 2 – Basalt fibers (photographed by the author, sample obtained from Technobasalt Company)

Figure 3 - Basalt rods (photographed by the author, sample obtained from Technobasalt Company)

With basalt roving, we can produce fibers as seen on Figure 2 of different lengths and thicknesses, depending on the desired characteristics and properties of the concrete. From these fibers basalt rods of different diameters (on Figure 3) can be produced that can compete steel bars in terms of performance (Gulik, Biland, 2012).

The properties of basalt are shown in the Table 2 below. It is seen on Table 2 that the temperature parameters of basalt are suitable for becoming a reinforcing agent. The temperature at which concrete loses a large proportion of its strength is also an acceptable working temperature for basalt. Experiments performed in Reykjavik University compared thermal stability of carbon fibers, glass fibers and basalt fibers. After heating these fibers for 2 hours at 1200 °C and then cooling for 1 day carbon fibers had lost most of its strength, glass fibers had lost partially and basalt fibers showed no change during that time retaining all of their mechanical integrity intact (Ólafsson, Þórhallsson, 2009) (Sim, Park, Moon, 2005).

Sustained operating temperature, (°C)	800
Minimum operating temperature, (°C)	-260
Melting temperature, (°C)	1450
Density, (g/cm3)	2.8
Filament diameter, (microns)	13-20
Tensile strength, (MPa)	4200
Elastic modulus, (Gpa)	89
Elongation at break, (%)	3.15
Sound absorption coefficient, (%)	0.9-0.99

Table 2 – Properties of basalt fibers – Information from Gulik, Biland, 2012

The reinforced concrete with basalt fiber has following advantages:

- High chemical and corrosion resistance;
- Longevity (it is actually a stone);
- High abrasion resistance;
- High shock resistance;
- High water resistance;
- High frost-resistance.

Tests performed with basalt-concrete composites have shown increase in compressive strength. The optimum has been found to be with a volume fraction of 0.5% of basalt in concrete which showed a 12% increase while increasing modulus of elasticity of the mixture. Tests performed by

Technobasalt-Invest LLC using 2 kg of basalt achieved a larger increase in tensile and compressive strength, correspondingly 4,76 MPa and 39,1 MPa, compared to 25 kg of steel fibers with results of 4,07 MPa and 38,6 MPa. On the other hand workability of concrete including basalt fibers decreased as proven by a flow table test (Raj, 2014) (Technobasalt-Invest, 2011).

The cost-efficiency is another important advantage of basalt fiber over other types of fiber. Based on economic assessments made by Technobasalt-Invest LLC and considering the other alternatives, the use of basalt fiber can be several times cheaper than using metal fiber. The ASTM standard, C637-09 Standard Specification for Aggregates for Radiation-Shielding Concrete, specifies the list of aggregates for radiation-shielding concrete. Within this standard is listed several types of aggregates such as natural mineral aggregates of either high density or high fixed water content, aggregates that contain or consist of materials such as barite, magnetite, hematite, ilmenite, and serpentine, synthetic aggregates such as iron, steel, ferrophosphorus and boron frit. According to the results of this study, basalt fiber stands as a very good reinforcement for NPP and still cheaper than the alternatives and already in use materials (Gulik, Biland, 2012).

3. Theory of radiation shielding

Radiation interaction with matter has to be taken into account for the building materials in nuclear facilities. How that interaction occurs and what are the results varies depending on the type of radiation. For example electrons in matter can interact with gamma ray or photon radiation resulting in scattered radiation. Energy can also be absorbed which can result in emission of heat, gamma radiation or charged particles. Alpha- and beta- particles are directly ionizing particles. They can easily be stopped as they interact strongly with matter. Indirect ionizing particles that are not charges themselves like neutrons, gamma ray and X-ray photons cause ionization by secondary particles. As they do not interact well with matter they become the main problem for radiation shielding in nuclear facilities (Kaplan, 1989).

The main problem with radiation shielding is due to photon and neutron interactions with matter. Photons interact with matter in three different ways resulting in:

- Photoelectric effect
- Pair production
- Compton scattering.

Photon interaction with an electron binds to an atom that has larger energy than that binding energy of that electron results in the ejection from the atom. This process is the most important photon absorption process at low photon energies. The importance of photoelectric effect increases as the atomic number of the absorbing material increases while the energy of photons decreases. Photoelectric effect may start other forms of radiation, the secondary radiation is not important and can be disregarded (Kaplan, 1989).

Pair production is a process where a photon is converted into a pair of electron and positron. For this to occur the energy of photon has to be bigger than 1.02 MeV when the rest mass of the electron is equivalent to 0.51 MeV. The probability of pair production rises with the atomic number. Even though pair production is followed by secondary radiation from annihilation of positrons, these photons are unimportant and pair production is considered a true absorption process just like photoelectric effect (Kaplan, 1989).

Compton scattering is a process where photon is perceived to be colliding elastically with an electron. As a result, the photon loses some of its energy and the electron receives the energy that is deflected from its original direction. Compton scattering is one way of photon losing enough energy to be absorbed through photoelectric effect. While other two absorbing effects are sufficient for absorbing the photon, Compton scattering is not, as new photon might not be appreciably deflected or degraded in energy. The cross-section for Compton scattering is proportional to the atomic number in target material. In addition, Compton scattering has bigger occurrence probability than two previous ones on a wide range of photon energies except the case of heaviest elements (Kaplan, 1989).

In case of neutrons, the interaction in material is with the nuclei. The interactions are very dependent on the neutron's kinetic energy. Neutrons described by their kinetic energy can be divided into:

- Thermal neutrons – neutrons that are in equilibrium with their surrounding atoms or molecules.
- Epithermal neutrons –neutrons that have greater energy than thermal neutrons.
- Slow neutrons – neutrons that have energies up to 10 eV (sometimes up to 1000 eV).
- Resonance neutrons – neutrons with energy between 1 and 300 eV and are captured in the resonance of a nuclide.
- Intermediate energy neutrons – neutrons that have energies between slow and fast neutrons.
- Fast neutrons – neutrons that have energies between 0.5 MeV and 20 MeV.
- Very fast neutrons – neutrons that have energies greater than 20 MeV.

One way of neutron reacting with matter is by taking part in nuclear reaction where neutron collides with a nucleus of an atom and as a result new nucleus is created that can decay to a nucleus of another element and an emitted particle (Kaplan, 1989).

Another way is through elastic scattering where in the aftermath of a collision between neutron and nucleus the residual nucleus is in a ground state and the only energy absorbed is in the form of kinetic energy. This is especially important for light nuclei which can absorb large sums of energy. In inelastic scattering the residual nucleus is in excited state. This energy is emitted by the nucleus in the form of one or more gamma rays. The significance of inelastic scattering increases with mass number of the target nucleus (Kaplan, 1989).

In neutron capture the neutron is absorbed by a nucleus resulting in an intermediate nucleus that is in an excited state. The intermediate nucleus decays within a short period of time by emitting photons or charged particles. This reaction mostly occurs with neutrons with thermal energy capacities (Kaplan, 1989).

The interaction between a radiation particle and a matter is probabilistic. This probability is described by linear attenuation coefficient μ, for a certain way of interaction per unit path-length. Linear attenuation coefficient is proportional to the number of atoms per unit volume of the shielding material. The proportionality constant is called the microscopic cross-section (Kaplan, 1989).

The linear attenuation coefficient is also dependent on the density ρ of the material. It is derived by creating mass attenuation coefficient μ/ρ to lose this dependence (Kaplan, 1989). These coefficients are available in tables for separate elements made by Hubbell and Seltzer in 1995 and also in the XCOM database. In this work, mass attenuation coefficients are calculated by the software called WinXCOM that is described below (Hubbell, Seltzer, 1995).

For materials with complex structures such as concrete, effective atomic number and effective electron density are convenient parameters representing x-ray and γ-ray interactions because in the case of gamma rays the increase in linear attenuation coefficient is in parallel with the rise in effective atomic number. As x-rays and γ-rays mainly interact with electrons, then the probability of interaction is describable with the density of electrons (Manohara, Hanagodimath, Gerward, 2009).

To calculate effective atomic numbers and effective electron density we first have to find molar fraction f_i normalized so that $\sum f_i = 1$ in for each element i in the mixture as generally mass fraction is given. Molar fraction is calculated using equation:

$$f_i = \frac{\frac{W_i}{A_i}}{\sum \frac{W_i}{A_i}}$$

Where $W_i$is the mass fraction of element i and $A_i$is the atomic mass of element i. Using the molar fractions for each element in the mixture we can calculate mean atomic mass and mean atomic number.

$$\langle Z\rangle = \sum f_i\, Z_i$$

$$\langle A\rangle = \sum f_i\, A_i$$

Where $\langle Z\rangle$ is mean atomic number, Z_i is atomic number of element i and $\langle A\rangle$ is mean atomic mass. Using these we can calculate the effective atomic number as described in Manohara article:

$$Z_{eff} = \frac{\sum f_i\, A_i \frac{\mu}{\rho}_i}{\sum f_i \frac{A_i}{Z_i} \frac{\mu}{\rho}_i}$$

For calculating effective electron density we can use equation described in the same article:

$$N_{eff} = N_A \frac{Z_{eff}}{\sum f_i A_i} = N_A \frac{Z_{eff}}{\langle A\rangle}$$

Where N_A is Avogadro constant (Manohara, Hanagodimath, Gerward, 2009).

4. Software

4.1 XCOM and WinXCOM

Various scientific, engineering and medical applications require data on absorption of X-rays and gamma-rays. Cross sections and mass attenuation coefficients for elements, number of compounds and mixtures are readily available in tables, such as Hubbell and Seltzer (1995). Between 1987 and 1999, Berger and Hubbell developed a software called XCOM. XCOM is a web-based software that calculates mass attenuation coefficients or photon interaction cross-sections for any element, compound or mixture at energies from 1 keV to 100 GeV. The idea behind XCOM software is saving time from manual work of interpolating tabulated values and using mixture rule. This software is later transformed under the name WinXCom by Gerward et al. (2001) and Gerward et al. (2004) into Windows platform with added capabilities. WinXCom is able to generate cross-sections or attenuation coefficients on an approximately or logarithmically spaced standard XCOM energy grid, or on a user-specified grid, or for a mix of both grids. Both softwares are very convenient alternatives to manual calculations to generate total cross sections, attenuation coefficients as well as partial cross sections for various interaction processes, such as incoherent and coherent scattering, photoelectric absorption and pair production, for elements, compounds and mixtures as needed. Both softwares work on the principle of input the weight fractions of the constituent elements. In addition, mass attenuation coefficients can also be directly calculates for any mixture of given chemical compounds in WinXCom (Hubbell, Seltzer, 1995) (Hubbell, Seltzer, 2004) (Berger, Hubbell, 1987/1999) (Gerward et al. 2001) (Gerward et al. 2004).

5. Results and discussion

Using knowledge about basalt composition obtained from correspondence with HHK Technologies (USA) and concrete sample from NIST (Hubbell, Seltzer, 2004) database, the following composition for basalt with main compounds are obtained:

Table 3 - The chemical composition of basalt fiber.

SiO_2	TiO_2	Al_2O_3	Fe	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	S	Cl
0,4947	0,0266	0,1555	0,1022	0,0020	0,0479	0,0825	0,0428	0,0174	0,0089	0,0004	0,0001

Table 4 - The chemical composition of concrete from NIST (Hubbell, Seltzer, 2004) database

H	C	O	Na	Mg	Al	Si	K	Ca	Fe
0,0221	0,0025	0,5749	0,0152	0,0013	0,0200	0,3046	0,0100	0,0430	0,0064

In order to determine the amount of concrete to be used in the calculations for radiation shielding HHK Technologies was consulted. For the company states that 1kg of basalt and 6 kg of basalt in a concrete mixture are the usual amounts to use. In order to observe a linear change from the amount of basalt in the concrete calculations for 15 kg and 20 kg of basalt per one cubic meter of concrete are also added. The calculated mass percentages of main elements in the mixture are presented in the Table 5.

With this data mean atomic number, mean atomic mass, effective atomic number and effective electron density were calculated. Min and max in effective atomic number and effective electron density columns represent the minimal and maximal value for corresponding mixture. The results are shown in Table 6:

	1 kg	2 kg	3 kg	4 kg	5 kg	6 kg	10 kg	15 kg	20 kg
H	2,209E-2	2,208E-2	2,207E-2	2,206E-2	2,205E-2	2,200E-2	2,200E-2	2,196E-2	2,191E-2
C	2,483E-3	2,482E-3	2,481E-3	2,480E-3	2,479E-3	2,478E-3	2,473E-3	2,468E-3	2,463E-3
O	5,749E-1	5,748E-1	5,748E-1	5,747E-1	5,747E-1	5,746E-1	5,743E-1	5,741E-1	5,738E-1
Na	1,522E-2	1,522E-2	1,523E-2	1,524E-2	1,524E-2	1,525E-2	1,528E-2	1,532E-2	1,535E-2
Mg	1,278E-3	1,290E-3	1,302E-3	1,314E-3	1,326E-3	1,338E-3	1,386E-3	1,446E-3	1,505E-3
Al	1,998E-2	2,001E-2	2,003E-2	2,006E-2	2,009E-2	2,012E-2	2,022E-2	2,036E-2	2,049E-2
Si	3,046E-1	3,046E-1	3,045E-1	3,045E-1	3,045E-1	3,044E-1	3,043E-1	3,042E-1	3,040E-1
P	1,714E-6	3,427E-6	5,139E-6	6,849E-6	8,557E-6	1,026E-5	1,708E-5	2,556E-5	3,401E-5
S	1,746E-7	3,490E-7	5,233E-7	6,974E-7	8,714E-7	1,045E-6	1,739E-6	2,603E-6	3,401E-6
Cl	8,731E-8	1,745E-7	2,617E-7	3,488E-7	4,358E-7	5,227E-7	8,697E-7	1,302E-6	1,732E-6
K	1,005E-2	1,005E-2	1,005E-2	1,005E-2	1,005E-2	1,006E-2	1,006E-2	1,007E-2	1,008E-2
Ca	4,296E-2	4,297E-2	4,297E-2	4,298E-2	4,299E-2	4,299E-2	4,302E-2	4,306E-2	4,309E-2
Ti	6,958E-6	1,391E-5	2,086E-5	2,780E-5	3,473E-5	4,166E-5	6,931E-5	1,037E-4	1,380E-4
Mn	6,762E-7	1,352E-6	2,027E-6	2,701E-6	3,375E-6	4,049E-6	6,736E-6	1,008E-5	1,341E-5
Fe	6,468E-3	6,501E-3	6,533E-3	6,566E-3	6,599E-3	6,632E-3	6,762E-3	6,924E-3	7,086E-3

Table 5 - Chemical composition of concrete with basalt fibers

	<Z>	<A>	Z_{ef} min	Z_{ef} max	N_{ef} min	N_{ef} max
1	7,09	13,93	5,68	13,33	2,46E+23	5,76E+23
2	7,09	13,93	5,68	13,33	2,46E+23	5,76E+23
3	7,10	13,93	5,68	13,33	2,46E+23	5,76E+23
4	7,10	13,93	5,68	13,34	2,46E+23	5,76E+23
5	7,10	13,94	5,69	13,34	2,46E+23	5,76E+23
6	7,10	13,94	5,69	13,34	2,46E+23	5,76E+23
10	7,11	13,96	5,70	13,36	2,46E+23	5,76E+23
15	7,11	13,96	5,70	13,36	2,46E+23	5,76E+23
20	7,11	13,97	5,70	13,37	2,46E+23	5,76E+23

Table 6 - Mean atomic mass, mean atomic number, minimum and maximum of effective atomic numbers and minimum and maximum of effective electron density.

For better understanding of effective atomic numbers dependence on photon energy, the following graphs 1-4 describing dependence respectively for mixture with 1 kg, 6 kg, 15 kg and 20 kg were obtained.

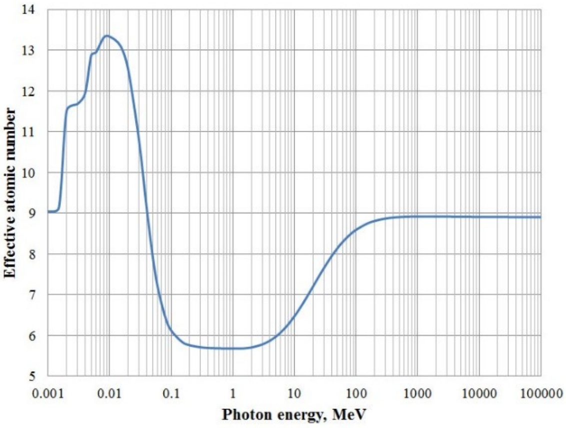

Figure 4 - Effective atomic number for concrete with 1 kg of basalt fibers.

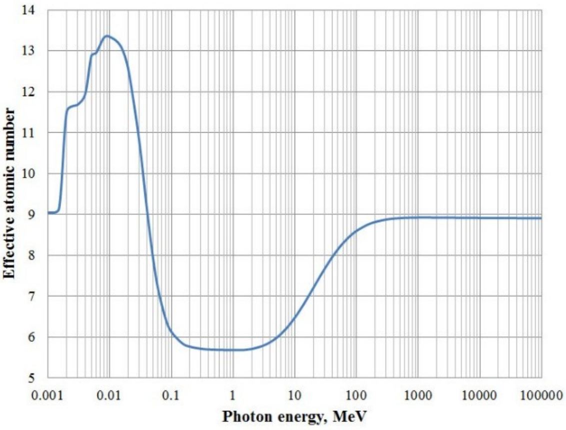

Figure 5 - Effective atomic number for concrete with 6 kg of basalt fibers.

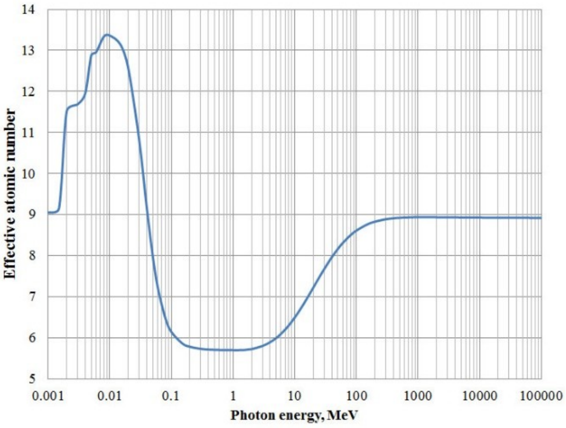

Figure 6 - Effective atomic number for concrete with 15 kg of basalt fibers.

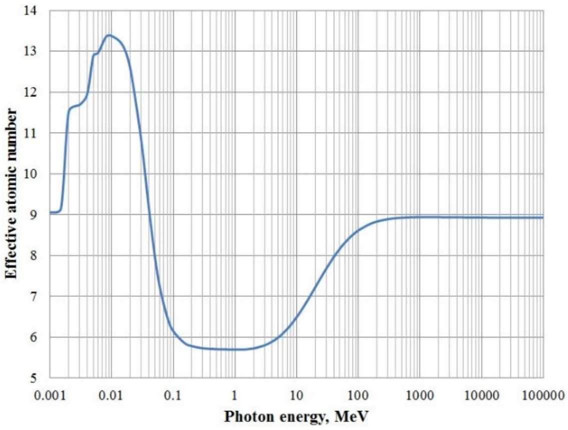

Figure 7 - effective atomic number for concrete with 20 kg of basalt fibers.

As seen from the table and the graphs there isn´t much difference between 1 - 20 kg of basalt additions but there is still an increase. It is clearly seen that effective atomic number is energy dependent.

6. Conclusion

This thesis describes the main issues with using concrete in nuclear energy applications and suggests one way to improve the radiation shielding properties of concrete. In this work, we can see that basalt fibers have properties suitable for use in nuclear energy applications and could improve the overall construction quality, durability and safety. Basalt is distributed evenly in concrete as it has more or less similar specific gravity as concrete. Better heat and fire resistance is shown by basalt fibers in comparison to glass or carbon fibers. The working temperature for basalt is higher than needed for the degradation of concrete. As basalt fibers are water and corrosion resistant, problems related to these parameters are solved. The chemical resistance, especially alkali resistance, of basalt fibers must be further studied.

As a part of this research, the effective atomic number and effective electron density to evaluate the suitability of basalt for radiation shielding properties are also calculated. From calculations it is seen that all gamma-ray attenuation coefficients increase with addition of basalt fibers into concrete for every cement-basalt composite. Also the effective atomic number increases with the addition of basalt fibers into concrete.

The need for basalt fiber in concrete is smaller than the need for metal fibers making it a cheaper, thus a better cost-efficient option.

The results show that basalt fiber reinforced concrete have improved shielding properties in comparison with regular concrete against gamma rays. This result is based on a regular concrete with only basalt fiber reinforcement. We estimate that with addition of standard aggregates for radiation shielding concrete, such as barite, magnetite or hematite, the shielding properties will increase exponentially.

Basalt-betoon komposiidi gamma-varjestuse parameetrite arvutuslik uuring tuumaenergeetika jaoks

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7. Kokkuvõte

Antud bakalaureusetöö peamine eesmärk oli uurida probleeme, mis esinevad betooni kasutamisel tuuma energeetikaga seotud rakenduses, ning kaaluda basaltkiudude kasutamist nende lahendamiseks. Töö käigus sai kirjanduse põhjal uuritud betooni tõmbe- ja survetugevuse muutust segule basaltkiudude lisamisel. Antud tööst paistab, et basaltkiud parandavad betooni vastupidavust ja eluiga, olles seega sobivad vastupidavat betooni vajavates rakendustes. Tänu sellele, et bassaldi ja betooni suhtelised tihedused on sarnased, jaotub basalt betooni segus ühtlasemalt ning ei vaju tahkumise käigus põhja või ei tõuse pinnale, tagades seelläbi ühtlasema tugevusjaotuse. Basalt on vastupidav ka temperatuuri tõusule ning korrosioonile. Keemilist tugevust on antud teema juures aga vaja edasi uurida.

Põhinedes uuringutel on näha, et basaldi kiude on vaja betoonile lisada ligikaudu 10 korda vähem kui teraskiude, et saavutada sarnane kasv betooni tugevuses. Sellest lähtuvalt saab järeldada, et basalt on odavam lahendus mõranemiste vastu kui teras.

Hindamaks basalt-betoonkomposiidi sobivust radiatsiooni varjestamiseks sai antud töö raames arvutatud materjali effektiivset aatomnumbrit ja effektiivset elektrontihedust. Arvutustest oli näha kõigi gamma-kiirguse nõrgestumisparameetrite kasvu basaldi kiudude koguse kasvamisega. Samuti oli näha effektiivse aatomnumbri kasvu.

Tuginedes töö käigus saadud andmetele võib öelda, et basaldi lisamisega betooni omadused paranevad lähtudes tuumaenergeetika vaatenurgast. Kuigi muutused olid antud arvutustes väikesed, tuleb arvesse võtta, et arvutused on läbi viidud kasutades tavalist betooni koostist ilma lisanditeta.

Antud teema raames on kindlasti vaja veel sooritada edasisi uuringuid ka neutron-kiirguse osas ning sooritada mõõtmisi, et leida kinnitust arvutustele.

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Computational investigation of gamma shielding behavior of cement-basalt composite for nuclear energy applications

Supervised by Alan Henry Tkaczyk, Volodymyr Gulik, Cagatay Ipbüker

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