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A Case Study of Radiation Shielding Structure for Cold Neutron Guide at HANARO

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1 ABSTRACT

This paper aims to describe the key factors regarding the design and fabrication of heavyweight concrete as a shielding material. The differences, when compared to the concrete shielding blocks that are normally stacked around neutron guides, are not only the need for a seismic integrity as a structural material, but also a radiation shielding effect for the neutron and gamma rays from the cold neutron guides. In general, heavyweight concrete is not available as a normal product. That is why this study was conducted, namely to fabricate a shielding material that meets the technical requirements. Conclusively, a fabrication procedure has been derived from a mix proportion design and a mock up test. The radiation shielding structure has been installed at the designated place for the neutron guides in HANARO. Although there are many kinds of difficulties in a radiation controlled area, all the work was successively conducted without any technical violations by using the developed procedures. It is hoped that this study will be a useful practice for other cases that require high density heavyweight concrete to satisfy seismic integrity as well as provide radiation shielding.

2 INTRODUCTION

HANARO, which is a research reactor with a thermal power of 30 MW, has been operating since 1995. The reactor was designed for multi-purpose use in various science and engineering fields such as material irradiation, nuclear fuel irradiation, neutron scattering, neutron radiography as well as neutron transmutation doping for silicon. All the aforementioned purposes, except for the Cold Neutron Source (CNS), have been developed successfully for their inherent aims. The development of the CNS is a final project to complete the overall design purposes of HANARO. In order to implement the final goal, a CNS project has been underway since 2003. It is also intended to enhance the neutron science research area, and utilization of HANARO, as a research reactor.

This paper intends to introduce the key factors regarding the design and fabrication of heavyweight concrete as a shielding material. Although concrete shielding blocks are normally piled up around neutron guides, the shielding room should be required to have a seismic integrity as a structural material and a radiation shielding effect to prevent the neutron and gamma rays from the cold neutron guides. Generally, heavyweight concrete higher than 3.5 g/cc in density is not available as a normal product. In addition the concrete to be used in nuclear facilities shall be severely qualified for all the processes of batch plant. That is why this study was conducted, namely to design and fabricate a shielding material that meets the design requirements and technical standards required by the regulatory body.

The cold neutron guide should be installed inside a biological shielding that is assumed to be an ideal absorber for neutron and gamma rays. It means that all the radiation is absorbed immediately without the production of secondary radiation. HANARO user facilities have been separated into four kinds of radiation regions such as 6000, 7000, 8000, and 9000 regions depending on the biological shielding for people who are working inside the radiation controlled area. The radiation levels of those regions are respectively limited to equal to or less than 6.25, 12.5, and 500 μSv/hr. But the 9000 region is set higher than 500 μSv/hr. People who have received the working permission are able to access all the regions except for the 9000 region. Because the 9000 region is restricted to any person when the reactor is operating, this region should be isolated by the shielding structure.

3 DESIGN REQUIREMENTS

Based on the suggested material according to the radiation level of the 9000 region, a simulation for the shielding effect has been carried out to evaluate the appropriateness of the proposed design. According to the simulation that was carried out by help of the Monte Carlo Method, the shielding materials were designed by using two different kinds of concrete. The first one is a heavyweight concrete of more than a 3.5 g/cc density and the other one is around a 2.3 g/cc density. As mentioned, many kinds of instruments operate around beam ports of reactor, and there is not enough space to accommodate a shielding structure in an existing reactor hall. It has been confirmed that the wall thickness of the shielding Room B of Figure 1 should be less than 800 mm. In order to install a concrete wall that satisfies the radiation shielding effect in such a small space, there is no other way except for the concrete to have a more than a 3.5 g/cc density. The Room A installed in the guide hall, which was newly constructed to accommodate cold neutron instruments at the end of 2008, used a 2.3 g/cc density in normal concrete. To realize the same shielding effect at the radiation condition of the 9000 region, the concrete wall of Room B increased to twice the thickness of Room A. So, it has been determined that the thickness of its front and side walls are respectively 2000 and 1600 mm. This paper is focused on the practical characteristics of mix proportion design for heavyweight concrete.

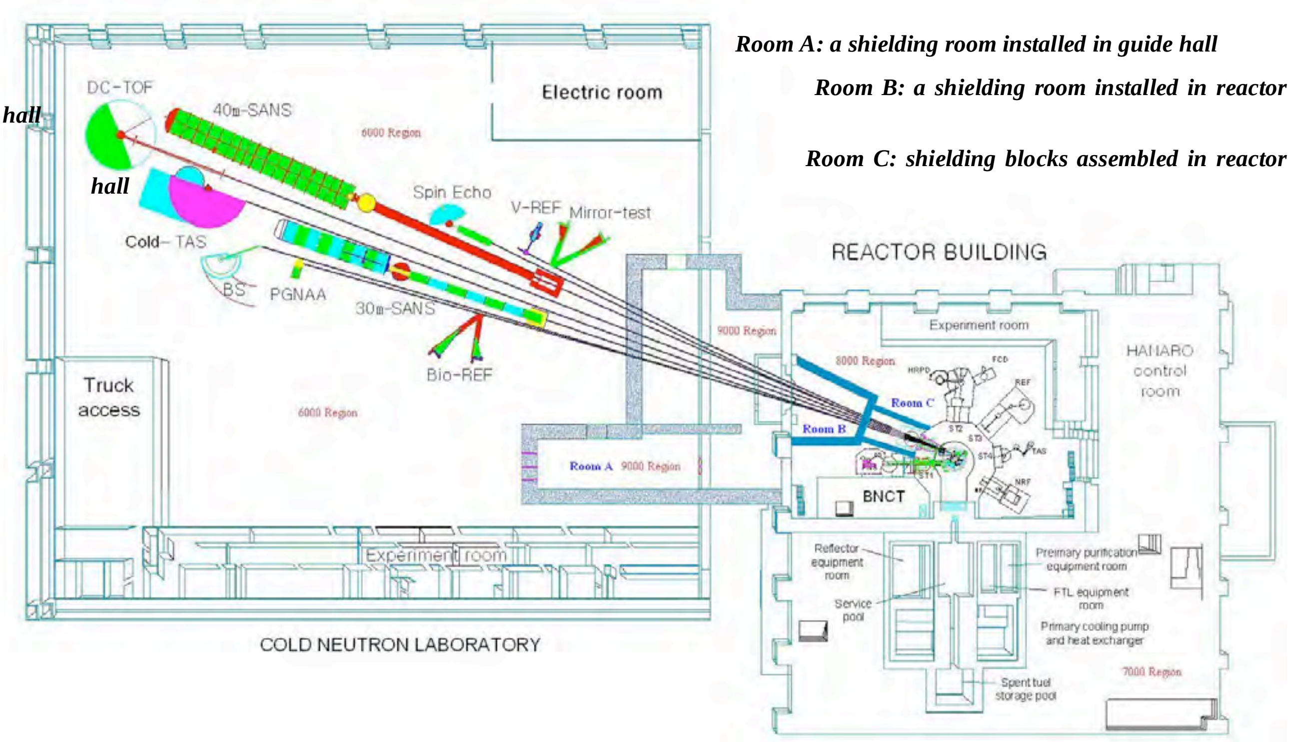

Figure 1. Guide shielding room arrangement at HANARO facilities

A 3-story steel structure building was designed to accommodate the systems and components for the cold neutron research facility located in the existing reactor hall. The ground floor of the building serves as a guide shielding room as well as an infrastructure. The neutron guide goes to the neutron guide hall located in the direction of the north-west side of the reactor building. It penetrates through the exterior wall of reactor confinement so it interfaces the existing structure with the guide shielding room in structural behaviour under the seismic condition. That is why the guide shielding room was classified in seismic category and non-nuclear safety (NNS). So, it should be seismically qualified for Safe Shutdown Earthquake (SSE) response spectrums defined in HANARO site acceleration, 0.2g horizontal. It turned out that the concrete will be required to have a compressive strength of much more than 35 MPa at 28 days after placing through out a dynamic structural analysis by FEM subjected to design floor response spectrums. Also, it was designed to optimize the interferences with the existing structures or facilities in the reactor hall. An appropriate height and space of each floor were reflected for the structural design to avoid any problem in installation or maintenance work.

The guide shielding room is designed to reinforce concrete according to building code requirements for structural concrete and commentary by ACI 318. The mix proportional design of concrete should be governed under the requirements of standard practice for selecting proportions for normal, heavy-weight, and mass concrete by ACI 211.1 and specifications for structural concrete by ACI 301. The total volume required for the guide shielding room is estimated at around 130 m^3. Even though the required volume is not too much to produce by a commercial batch plant, it could not be possible to do it with the small mixer that is usually used in a laboratory. To be kept at a uniform quality of production, there is no way except for the concrete to be produced by commercial batch plant. Table 1 shows the basic requirements for fresh and hardened concrete to be applied by ACI code.

Table 1. Quality criteria for heavyweight concrete

Item	Property	Test code	Criteria	Unit	Remarks
Fresh concrete	Sump	ASTM C 143	4±1	inch	Fresh
	Air content	ASTM C 231	2.5±1	%	Non-air
	Density	ASTM C 138	> 3.5	g/cc	Fresh
	Chloride content	ASTM C 1218	< 0.3	kg/m^3	Fresh
Hardened concrete	Mould	ASTM C 31	1 5x30	cm	Cylindrical
	Compressive strength	ASTM C 39	> 35	Mpa	28 days

4 MIX PROPORTION DESIGN

The radiation shielding effect would be mostly affected by the physical and chemical characteristics of the concrete. Generally, it is known that the shielding effect depends on the kinds of aggregates that compose the concrete. American National Standard (ANS) provides several cases as an example of typical compositions of representative concretes after curing. At the beginning of this project, magnetite was considered as a coarse aggregate, but it did not have the proper density as a coarse aggregate, namely at least higher than 4.0 g/cc in density. Therefore, barite composed of over 90% BaSo4 instead of magnetite was adopted as a coarse aggregate for the heavy concrete. The magnetite was mined in the South Korea but the barite was imported from China. Although there are available kinds of magnetite, which were imported from foreign countries such as India, Brazil, and Australia, higher than 4.0 g/cc in density, they did not have the required mechanical properties as a coarse aggregate. So, barite was finally adopted as a coarse aggregate.

Table 2. Mechanical properties of aggregates adopted for heavyweight concrete

Aggregate	Density (g/cc)	Fineness modulus	Absorption (%)	Soundness (%)	Passing 75 μm (%)	Clay content (%)
Fine (magnetite)	4.21	3.21	0.51	4.21	1.02	0.58
Coarse (barite)	4.30	6.80	0.50	3.27	0.17	-

In order to increase the density of the concrete, it is better for the air content contained in the concrete to be lower than normal. ACI provides that the air content is defined as 4.5±1.5% for a normal case and 3.5% maximum of an aggregate at 3/4 inch and a mild exposure condition. Also, in ACI 301, the air content may be additionally reduced by 1% in case of a compressive strength above 35 MPa. So, it has been determined that the air content at 2.5±1% might cause the density to be an average of 2% higher than normal. Although each element comprising the concrete satisfies their requirements, to lower the air content in the concrete is a key factor to greatly increase the inherent density of concrete.

It has been found that the heavyweight concrete satisfies the design requirements regarding its density. And, the other characteristics of a structural material such as the slump, compressive strength, air content, and chloride content have also satisfied enough of their design requirements. The normal Portland cement as a binder that meets ASTM C 150 type II or KS L 5201 is higher than 3.15 g/cc, and the fly ash is at least 2.22 g/cc in density. Table 2 shows test results regarding the mechanical properties selected for heavyweight concrete. According to ACI 211, the mix proportion design was processed by the following steps.

1) Step 1. choice of slump: 4±1 inch
2) Step 2. Choice of maximum size of aggregate: Barite < 3/4 inch, Magnetite
3) Step 3. Estimation of mixing water and air content: water153 kg/m^3, air content 1.5%
4) Step 4. Selection of water-cement materials ratio: 0.43
5) Step 5. Calculation of cement content: 356 kg/m^3, Fly ash 5%
6) Step 6. Estimation of coarse aggregate content: 10% lower than that of ACI 211.1 Table 6.3.6
   (It intends to improve the workability of high density concrete)
7) Step 7. Estimation of fine aggregate content: 58%
8) Step 8. Adjustment for aggregate moisture: Table 3 and Table 4
9) Step 9. Trial batch adjustment

The water-cement ratio of concrete has been kept as low as possible within proper workability and required strength. From the results of the trial batches, it has been determined that the properties of fresh concrete such as slump, air content, density, chloride content satisfied definitely their design requirements. The compressive strength of the test specimens, which were made from the trial batch, were measured by the method of ASTM C 39 when they arrived respectively at 3, 7, and 28 days after curing in cylindrical mould by ASTM C 31. The density and strength shows at least 3.53 g/cc and 47.2 MPa at 28 days. That means the proposed mix proportion was properly verified giving the material properties required for structural concrete.

Table 3. Developed mix proportion for heavyweight concrete

Max. size (mm)	Slump (in)	Air content (%)	W/C (%)	S/a (%)	Unit content (kg/㎥)					
					Water [W]	Binder [B]		Fine aggregate	Coarse aggregate	Ad.
						Cement [C]	FA			
20	4	1.5	43	58	153	338	18	1783	1320	8.5

Table 4. Test results for developed mix proportion through out trial batch

Slump (in.)		Air content (%)		Density (t/m^3)		Chloride content (kg/m^3)	Compressive strength (MPa)		
Initial	60min.	Initial	60min	Initial	60min	Initial	3 days	7 days	28 days
4.0	3.5	1.7	2.0	3.54	3.53	0.075	30.5	38.4	47.2

5 RESULTS OF MOCK-UP TEST

The shielding structure is designed to be placed inside a reactor building which was designed for containment to prevent any spread of nuclear substances to the atmosphere. There are several difficulties in installing the shielding room inside the reactor building, namely there is no proper way to transfer fresh concrete from outside into the reactor hall. Even though it has a truck access floor to carry freight in and out, the distance between the truck access and the designated place for the shielding room is over 60m. If it were normal concrete, it would be possible to transfer the concrete by normal pumping equipment over such a long distance. But heavyweight concrete may cause worse pumping when using normal equipment.

Moreover, it is expected that the concrete has poor workability and finishing. For these reasons, the proposed mix proportion was changed to provide greatly increased workability without the addition of excessive amounts of water. It is in accordance with guidelines for the use of high-range water-reducing super-plasticizers in concrete by ACI 212 and standard specifications for chemical admixtures for use in producing flowing concrete. Flowing concrete is defined by ASTM C 1017 as concrete that is characterized as having a slump greater than 190 mm while maintaining a cohesive nature. It can be placed so as to be self-leveling yet remaining cohesive without excessive bleeding, segregation, or abnormal retardation. Finally, the slump of concrete was changed into 8±1 inch by the addition of chemical admixtures by ASTM C 494 and super-plasticizers by ASTM C 1017. The final mix proportion was set as shown in table 5 below. Table 6 shows the test results of the final mix proportion with high range water reducing admixtures.

Table 5. Final mix proportion for flowing concrete by high range water reducing admixtures

Max. size (mm)	Slump (in.)	Air content (%)	W/C (%)	S/a (%)	Unit content (kg/㎥)					
					Water [W]	Binder[B]		Fine aggregate [S]	Coarse aggregate [G]	Ad.
						Cement [C]	FA			
20	8.0	1.5	43	58	153	338	18	1783	1320	10.0

Table 6. Test results of final mix proportion with high range water reducing admixtures

Slump (in.)		Air content (%)		Density (t/m^3)		Chloride content (kg/m^3)	Compressive strength (MPa)		
Initial	60min.	Initial	60min	Initial	60min	Initial	3 days	7 days	28 days
8.0	8.0	1.5	1.7	3.53	3.52	0.074	30.1	38.4	48.2

The mix proportion is necessary to maintain a homogeneous density in all parts of the concrete dump. After that, a mock up test was carried out to investigate the possibility of segregation, cracking by shrinkage, and thermal stress by hydration heat, and its workability. The mock up test was prepared with a half scale at the same height and thickness as the shielding structure to be installed for the neutron guides. From the results, there is no evidence of cracking induced by shrinkage as well as thermal stress after three months curing. Also, the heavyweight concrete, which was made by a commercial batch plant with a 100±25mm slump, can be transferred into a mold at a nearly 60m length by using normal pumping equipment. The distance was simulated under the same placing conditions of the reactor building.

Table 7. Developed mix proportion for mock-up test

Mixture no.	W/B	S/a	Unit content (kg/m³)						
			Water [W]	Binder [B]		Fine aggregate [S]	Coarse aggregate [G]	Ad. 1[1] (C×%)	Ad. 2[1] (C×%)
				C	F/A	Magnetite	Barite		
1	42	53	160	381	-	1600	1453	2.2	-
2		55	157	374	-	1673	1402	2.2	-
3				348	26	1666	1393	2.4	-
4		57				1725	1333	2.5	-
5						1725	1333	2.4	-
6						1725	1333	2.4	0.3

1) Ad. 1: ASTM C 494 Type F, Ad. 2: ASTM C 1017 Type II

Table 8. Results of mock-up test

Mixture no.	Slump (mm)	Air content (%)	Unit weight (g/cc)	Compressive strength (MPa)		
				3 days	7 days	28 days
1	190	1.5	3.51	30.3	40.6	49.1
2	90	1.8	3.52	35.9	44.4	50.7
3	135	1.8	3.51	33.3	43.3	48.1
4	130	1.6	3.54	29.3	37.2	47.4
5	110	2.0	3.54	29.9	39.1	48.9
6	190	1.8	3.54	28.2	38.2	49.2

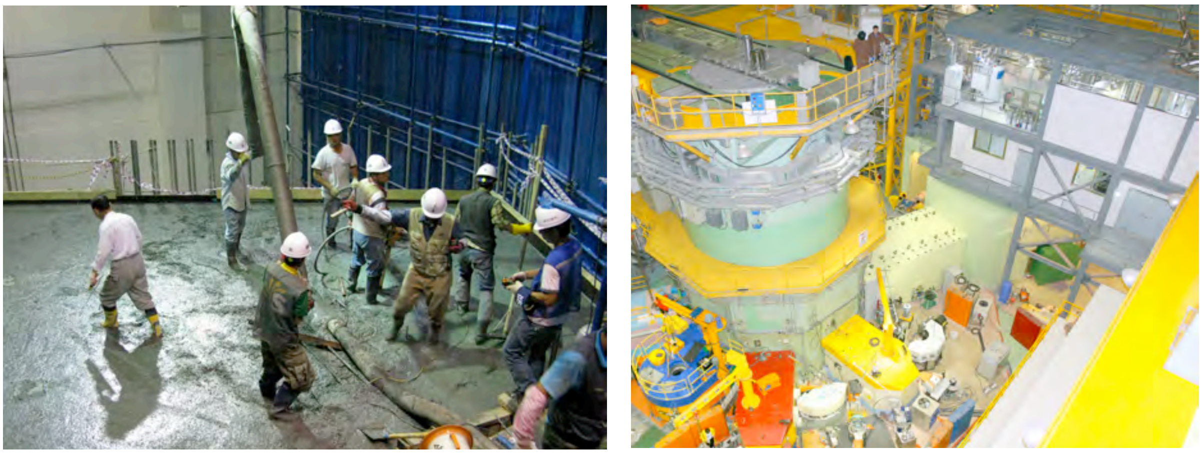

Figure 2. Placing of heavyweight concrete and completed shielding room in reactor hall

On the other hand, because this shielding structure was designed with a thickness of 800 mm, we should consider controlling the thermal stress induced by the hydration heat up of the mass concrete. The heat up temperature when the concrete was being cured in the mock up test was acquired by embedded temperature sensors in the concrete. Also, an analysis to estimate the heat up temperature was carried out with a mixed proportion of the concrete. Based on the test and analysis results, thermal cracking might be induced at 1.5~2 days after placing. It turns out that the heat up decreases after 8 days. So, it should be resolved with protection layers, which are made of fabric normally used in curing concrete to retard the dry up speed of the water in the concrete just after a placing.

6 CONCLUSION

This paper is intended to introduce all the procedures regarding mix proportion design and verification of a trial batch of high density heavyweight concrete used for shielding structure. The shielding concrete should be of sufficient structural integrity for seismic load as well as the radiation shielding effect to prevent neutron and gamma rays from cold neutron guides. Through out the mix proportion design and fabrication of the heavyweight concrete, the findings are summarized as below.

A heavyweight concrete greater than 3.5 g/cc has been developed by composing barite as a coarse aggregate mixed with magnetite as a fine aggregate. Developed heavyweight concrete satisfied enough of the design requirements for a structural material such as the slump, compressive strength, air content, and chloride content.

An air content of 2.5±1% might cause the density to be an average of 2% higher than normal. To lower the air content of concrete is a key factor to greatly increase the inherent density of concrete.

To improve the workability, the mix proportion was changed to provide greatly increased workability without the addition of excessive amounts of water in accordance with guidelines for the use of high-range super-plasticizers. It has been determined that heavyweight concrete with 100±25 mm slump would be well transferred into a mould at a 60 m length by using normal pumping equipment.

The radiation shielding structure finally has been installed at the designated place for the neutron guides in HANARO in August 2008. Although there are so many kinds of difficulties in a radiation controlled area, all the work was successively conducted without any technical violations by using the developed procedures. It is hoped that this study will be a useful practice for other cases that require a high density heavyweight concrete to satisfy not only a seismic resistance but also a radiation shielding effect in nuclear facilities.

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