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Gamma Radiation Shielding Effect of Various Heavy Concretes Using Domestic Mineral Aggregates

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Abstract

This paper describes a detailed investigational performance on the gamma radiation shield effect of heavy concretes that were manufactured by the use of mineral ores produced domestically and which may be possibly applied for the biological shield design. Ten different kinds of mineral ores were collected for use as the aggregates, physical test and chemical analysis for them were carried out to select the aggregate with a better property. Through the experimental investigation on the shielding effect of various concretes with different combination of concrete components such as water-cement and fine-coarse aggregate ratios, it was possible to derive some criteria for the best condition being capable of obtaining the concretes with high density and good uniformity. Data on the shielding-effectiveness of the different concretes were obtained by performing collimated beam experiment using ^{60}Co gamma-ray.

Analyzing the shielding-effeciency, shielding-concrete specific gravity and biological shield cost, the optimum condition of yielding the best economic shielding design, with low cost and good spatial distribution to some extent was determined.

요 약

국내에서 산출되는 광물골재를 사용하여 방사선 차폐용 중차폐 콘크리트를 제조하고 감마선에 대한 차폐효능을 규명하는 동시에 방사선 차폐체로서의 활용가능성을 검토하였다. 10여종의 각기 다른 광물골재를 수집하여 방사선 차폐용 골재로서의 사용타당성을 검토하기위한 물리시험과 화학분석이 실시되었고 이 결과를 토대로 최적한 골재를 선택하여 중차폐 콘크리트가 제조되었다. 차폐용 콘크리트를 제조하는데 골재의 배합비, 물—세멘트 비율, 세골재, 조골재 비율 등을 달리해주므로써 방사선 차폐효과가 달라지는 현상을 실험적으로 구해 보았고 그 결과 차폐체의 비중이 높고 균질성이 좋은 중차폐체의 설계 조건을 유도해 낼수 있었다. 각기 다른 중차폐체에 대한 차폐효능 실험은 ^{60}Co 감마선원을 사용한 방사선 투과시험법으로 구했다. 실험을 통하여 중차폐체에 대한 방사선 차폐능과 차폐콘크리트의 비중, 차폐가격등을 분석하므로써 차폐설계상 최적의 공간배치로서 가장 경제적으로 차폐체를 설계할 수 있는 최적의 조건을 얻을 수 있었다.

I. Introduction

The increasing trend of facilities which handle radioactive materials on a large scale has brought up a serious problem of how to provide adequate shielding for the protection of the human body from radiation.

In view of the pressing need for developing adequate domestic shielding material, we have attempted in this experiment to exploit the possibility of utilizing various mineral ores of domestic production to meet the demand.

In general, requirements necessary for the radiation shielding material are as follows: Firstly, the material must have a large absorption coefficient for the radiation of interest and should readily be available with low price. Secondly, it must have a high degree of structural uniformity. Thirdly, it should have low expansiblity and high strength in its structure.

In this respect, concrete is an excellent material for radiation shielding. It is economical, stable and versatile. In addition, it may be used structurally. Shield thickness can be reduced by using denser concrete. This often results in overall saving in reactor construction and other shielding design.

In case of special purpose of radiation shielding, Steel, Tungsten and Uranium can be used as heavy aggregates. Mineral ores such as magnetite and barite, however, are more popular than those for producing heavy concrete because of economical factor.

One thing that should be taken into account in the construction of heavy concrete is that every possible effort should be made to raise its density by increasing amount of unit aggregate. On the other, we should not neglect to raise uniformity of the concrete by studying its workability.

In raising shield density, it is imperative to select aggregates containing a large amount of heavy element. The criteria for choosing aggregates are a high degree of density of the mineral ore being used and a uniform distribution of heavy element composition in the ore. Besides, the ore should be the one available
ore. Besides, the ore should be the one available
easily and economically.

The above stated factors have all been taken into consideration in this experiment. Ten different kinds of domestic minaral ores which could possibly be used as radiation shielding material were selected. With these aggregates, we have constructed several kinds of heavy concretes, and examined their shield effect against gamma radiation and attempted to grade them on the basis of economy and shielding effectiveness.

2. Cement and Aggregates Used in This Experiment.

(1) Cement

The cement used in this experiment was the starmarked, Portland cement of the Dong-Yang Cement Co. Its chemical compositions and physical properties are indicated in Table 1.

(2) Aggregates

Table 2 illustrates mineral samples selected from domestic ores in terms of their classification, the place of origin and analysis data. Granite here represents just the ordinary aggregate which is compared with other heavy aggregates.

Two types of grain size of the mineral samples were used in this experiment. One was of powder form with a grain size below 0.6 mm crushed at the mine and the other with a large grain.

Lead ore collected from the Woll-am mine contained about 40% of Pb and 4.6 g/cm^3 of average density and was the highest degree of density among the samples tested. But it was

Table 1. Chemical, Physical Properties of Portland Cement.*

Kind of Test	Contents			Value
Chemical Analysis	Ignition loss			1.85%
	Insoluble residue			0.19%
	SO_3			1.49%
	MgO			3.09%
	SiO_2			20.66%
	Al_2O_3			6.48%
	Fe_2O_3			3.14%
	CaO			63.08%
	Total			99.96%
Chemical Composition	3CaO. Al_2O_3			11.82%
	3CaO. SiO_2+3CaOAl_2O_3			59.28%
Physical Properties	Specific Gravity			3.14g/cm^3
	Fineness	Specific Surface		3050 cm^2/g
		Normal Consistency		22.4%
	Setting Time	Initial Set		2:05 (hours)
		Final Set		3:40 (hours)
	Soundness			0.56%
	Strength	Tensile Strength	3 days	20 kg/cm^2
			7 days	27 kg/cm^2
			28 days	34 kg/cm^2
		Compressive Strength	3 days	151 kg/cm
			7 days	205 kg/cm^2
			28 days	285 kg/cm^2

* Portland cement used in this experiment was produced from Dong Yang Cement Manufacturing Co. (1969. 7)
Test data was provided by the National Construction Research Institute.

found unsuitable for aggregates because of its high cost.

Magnetite whose ore has the average density of about 4.2 g/cm^3 seems to be the most promising choice for heavy concrete because of its sufficient domestic supply with relatively low cost.

Iron content in the magnetite fine grains can be raised up to 60% with the help of magnetic separation method. It can readily be used as high density of fine aggregate.

Heavy mineral sand produced in the outskirt of Chun-an is of grain size, about 0.3~0.6 mm and has the highest density (4.48 g/cm^3) among the fine aggregates. However, it is not recommendable as heavy aggregate on account of its high cost.

Slags available from waste product in the refining process at the Chang-hang Smelting plant may seem at first sight to be useful as coarse aggregate when crushed, since their cost is low and they also have Fe in composition.

Table 2. Summary of aggregates and its Chemical, Physical Properties

Kinds	Ore Size (cm)	Location of Mine	Specific Gravity (g/cm^3)	Water Absorption (%)	*Chemical Analysis (%)									TiO$_2$	SpotPrice** (1969. 12, Seoul) (won/ton)
					+Fe	FeO	Fe_2O_3	SiO_2	Pb	S	Mn	Ag (g/ton)	Zn		
Lead Ore	〉4cm	Woll-am, Kangwon	4.68	0.38	(25.03)	—	—	—	41.32	21.05	1.02	400	1.54	—	31,000
Magnetite	〉4cm	Choong-ju, Choongbuk	3.99	—	(34.80)	—	—	—	—	1.02	2.16	—	—	—	2,500
Magne-tite	〈5cm	Po-chun, Kyunggi	4.17	0.65	(53.59)	—	—	9.82	—	0.16	—	—	—	—	3,400
Magnetite	〉4cm	Mul-kum Kyung-nam	4.27	0.35	(53.87)	—	—	—	0.27	0.49	0.91	—	—	—	3,500
Lead Ore grain	〉0.6 mm	Choong-ju, Choongbuk	4.31	0.27	(24.49)	—	—	—	26.24	23.86	—	—	10.87	—	21,000
Magnetite grain	〉0.6mm	Mul-kum Kyung-nam	4 30	0.33	(54.45)	21.52	—	15.61	—	0.32	—	—	—	0.40	3,700
Magnetite grain	〉0.6mm	Po-chun, Kyunggi	4.30	0.45	(58.20)	—	—	—	—	—	—	—	—	—	3,700
Tungsten Ore	〉4cm	Sang-dong, Kan-gwon	2.96	0.41	(4.61)	5.19	0.41	42.62	—	—	10.22	—	—	—	2,400
Silver Ore	〈 5cm	Bu-pyung, Kyunggi	2 87	0 35	—	—	—	—	11.17	—	—	874	2.25	—	17,000
Slag	〈10cm	Chang-hang, Smelting Pl.	3.54	0.74	(25.34)	—	—	12.7	—	0.82	—	—	—	—	1,500
Granite	〈5cm	Mt. Bul-am, Seoul	2.60	0.85	—	—	~2.5	~67.0	—	—	—	—	—	—	500
Heavy Sand mineral	〉0.6mm	Chun-an, Choongnam	4.41	0.30	(31.78)	—	—	—	—	—	—	—	—	2.27	28,000
Sand	0.3~1.2 mm	Han river	2.50	1.20	—	—	—	—	—	—	—	—	—	—	330

* Chemical analysis was done at the Geological Survey of Korea.
** Estimated cost was based on % by cost of main element content in ore. (Source, Minig Association of Korea[1]
\+ Total Fe element in ore includes free iron plus Fe composition in FeO, Fe_2O_3

But the density of such slags is so largely subject to the nature of mineral ores and the refining process that they are inadequate as heavy aggregate.

3. Production of Concrete and Factors to Consider.

Among factors to be taken into consideration in connection with aggregate in the production of heavy concrete there are the mixing ratio, grain size, w/c ratio, uniformity, density, strength, radiation shielding effect, etc. To make a comparative analysis on these factors, we have first constructed ordinary concrete using ordinary aggregates, gravel and granite whose grain shape looks similar to that of heavy aggregates. By making use of findings of the first step, heavy concretes were made and proceeded to compare them in terms of their characters.

The aggregates used here were first crushed and then sorted out into 4 levels of grain size: coarse grain (20～40 mm), medium grain (10～20 mm), fine grain (5～10 mm) and powder form (0.6 mm or below): The distribution of grain size was followed on the basis of the standard grain curves adopted in Korean Standard F (KSF-2504)[2].

In Fugures 1 and 2 are shown the results of sieve analysis for ordinary aggregates and for heavy aggregates.

In this experiment, the standard slump tester (upper dia. 10 cm, base dia. 20 cm, height 30 cm) was used for testing workability. Cylindrical concrete samples with 15 cm in dia. and 30 cm in hight were made for the compressive strength test and the measurements performed with a period of 28 days in water curing.

For the comparative test, concrete block samples of 20 x 20 x 20 cm^3 were made and the gamma-ray transmission method was applied for measuring its uniformity and segregation of aggregate.

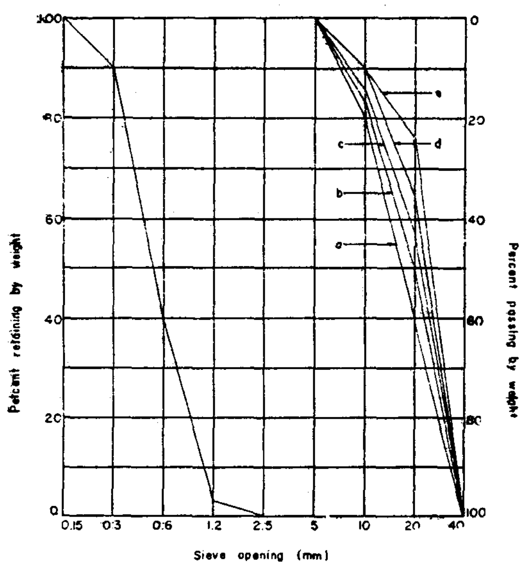

Fig. 1. Gradation curves of sieve analysis for ordinary aggregates.

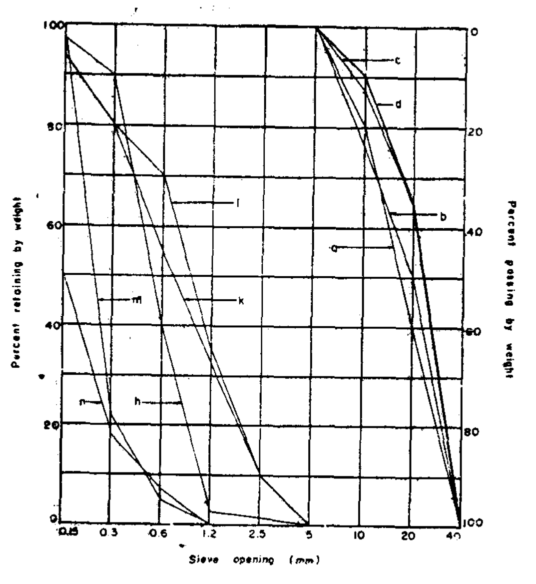

Fig. 2. Gradation curves of sieve analysis for heavy aggregates.

(a) Study of concrete combination, density and uniformity using ordinary aggregates.

The results of various concretes made up of both heavy aggregates and ordinary aggregates are shown in Table 3.

In Table 3, sample numbers 0–1, 0–3 and 0–4 indicate combinations of concrete in which S/A ratio was fixed by 35% and varied with the size of coarse aggregates. It is shown that density tends to increase with increasing portion of the coarse aggregates. As an exemple, in the case that the coarse aggregates with a grain size of 20∼40 mm were used, this tendency appeared above 60% in their portion. In the sample 0–5, the density reached the maximum when 65% of the coarse aggregates, size of 20∼40 mm was used with the S/A ratio at 27%. In the case of ordinary concrete, workability increases in proportion to the w/c ratio, while the volume density drops accordingly.

Figure 3 shows the results of uniformity measurement on ordinary concrete using the gamma-ray transmission method.

The uniformity improves with the increase of the w/c ratio and it can be interpreted as an indication of workability increase. The raising of the S/A ratio results in widening deviation rate in uniformity.

From samples G-1, to G-4. there was an example of ordinary concrete combination with granite as aggregate. The reason of using granite as an aggregate was that, since its crushed shapes are similar to those of heavy aggregate, it was believed they would provide some com-

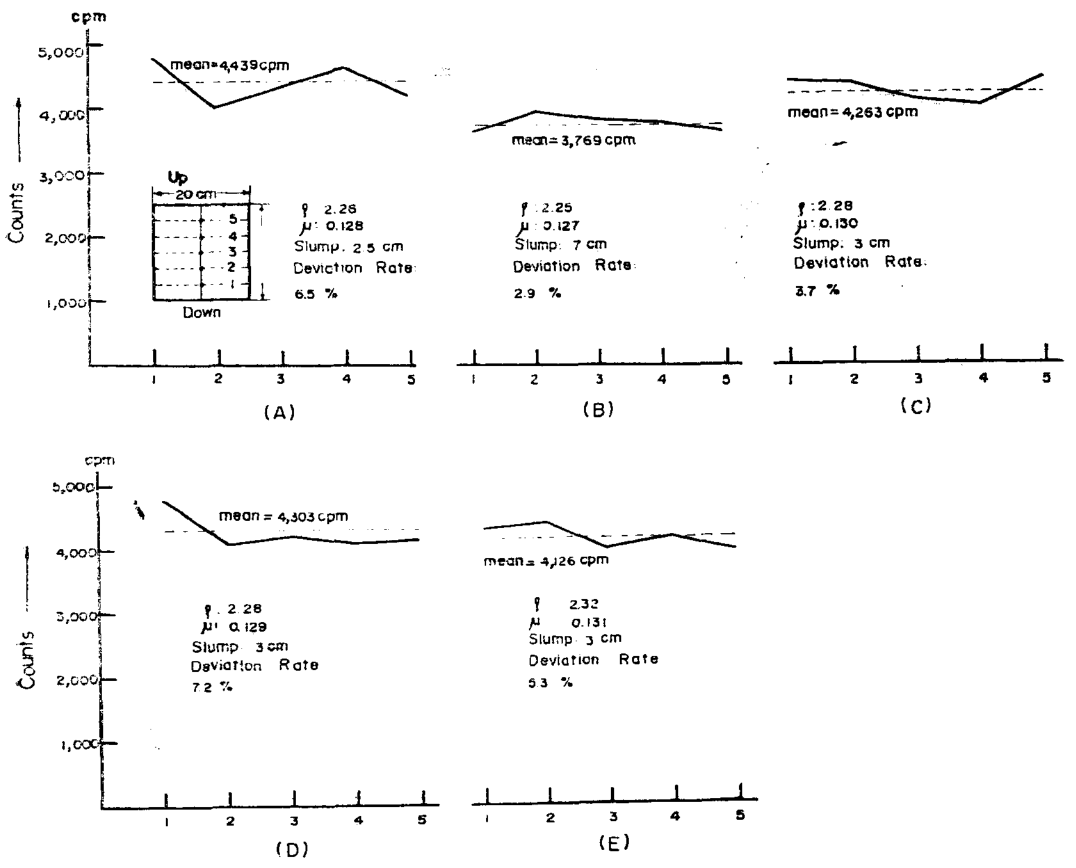

Fig. 3. Emergent Fluxes of ^{60}Co-Gamma-ray through Ordinary Concrete

Table 3. Experimental Data

Sample Number	Aggregates				Material		
	Find		Coarse		Cement (kg)	Water (kg)	Fine Agg. (kg)
O-1	Sand	(h)*	Gravel	(a)*	176	88	787
O-2	Sand	(h)	Gravel	(a)	172	114	769
O-3	Sand	(h)	Gravel	(c)	177	91	785
O-4	Sand	(h)	Gravel	(e)	177	91	785
O-5	Sand	(h)	Gravel	(d)	327	166	644
G-1	Sand	(h)	Granite	(a)	176	76	774
G-2	Sand	(h)	Granite	(a)	171	91	775
G-3	Sand	(h)	Granite	(a)	166	98	756
G-4	Sand	(h)	Granite	(b)	171	87	772
M-1	Sand	(h)	Magnetite	(a)	216	110	945
M-2	Sand	(h)	Magnetite	(a)	206	112	1,016
M-3	Sand	(h)	Magnetite	(a)	194	226	903
M-4	Mag. grain	(n)	Magnetite	(a)	275	140	1,209
M-5	Mag. grain	(n)	Magnetite	(a)	255	223	1,242
M-6	Magnetite	(k)	Magnetite	(h)	275	140	1,211
M-7	Mag. grain	(n)	Magnetite	(c)	295	150	925
M-8	Heavy sand	(m)	Magnetite	(c)	320	160	1,052
T-1	Mag. grain	(n)	Magnetite	(a)	272	136	1,190
T-2	Mag. grain	(n)	Magnetite	(d)	308	157	1,045
T-3	Lead Ore grain	(n)	Magnetite	(d)	316	158	1,046
P-1	Lead Ore grain	(n)	Lead Ore	(a)	284	145	1,243
P-2	Hem. grain	(n)	Hematite	(d)	322	165	1,105
H	Lead Ore grain	(n)	Hematite	(d)	320	160	1,061
K	Hem. grain	(l)	Magnetite	(d)	333	170	1,030
R-1	Sand	(h)	Slag	(a)	192	97	838
R-2	Mag. grain	(n)	Slag	(a)	220	110	960
A	Sand	(h)	Silver Ore	(a)	177	91	784
W	Sand	(h)	Tung. Ore	(a)	186	95	820

( )* Means grain size of aggregates used (Refer to Fig. 1 and 2)

parative data for determining uniformity and combination ratio in producing heavy concrete.

The experiment has disclosed a phenomenon that the improvement in uniformity is in proportion to the increase of w/c ratio. This is similar to that in the case of sand-gravel. Setting up the w/c ratio of 50% as a normal working condition, dropping of volume density was noted by raising up the ratio above the normal, and also uniformity was decreased with decreasing the w/c ratio below the normal. Thus, the w/c ratio 50% seems to be the most adequate. Fig. 4 shows the results of uniformity measurement on granite concrete using the gamma-ray transmission method. The optimum condition was obtained at w/c ratio 51% and 60% of grain size 20~40 mm.

(b) Production of heavy concrete and its characters.

The customary method adopted in manufacturing ordinary concrete were directly applied to make heavy concrete.

In Table 3, M-1, M-2, and M-3, was indicated

on the Concrete Combinations.

in 1 m³ Coarse Agg. (kg)	Water-Cement Ratio (%)	S/A Ratio (%)	Slump (cm)	Density of Concrete Calculated Value (g/cm³)	Density of Concrete Measured Value (g/cm³)	Compressive-strength, 28 Days (kg/cm²)**
1, 186	50	35	2. 5	2. 23	2. 26	174
1, 182	66	34	7	2. 24	2. 25	—
1, 198	51	35	3	2. 25	2. 28	162
1, 204	51	35	3	2. 26	2. 28	150
1, 241	51	27	3	2. 38	2. 32	177
1, 172	43	35	1	2. 19	2. 20	144
1, 186	51	35	3	2. 22	2. 26	—
1, 157	59	35	9	2. 18	2. 24	135
1, 201	51	35	3	2. 23	2. 24	140
1, 449	50	35	3	2. 72	2. 74	180
1, 363	55	35	7	2. 70	2. 72	163
1, 290	116	35	14	2. 61	2. 67	175
1, 796	51	35	3	3. 42	3. 42	213
1, 688	87	36	10	3. 41	3. 43	204
1, 826	51	35	3	3. 45	3. 49	210
2, 130	51	26	3	3. 50	3. 51	220
1, 892	50	31	3	3. 42	3. 44	140
1, 802	50	35	2. 5	3. 40	3. 41	183
1, 853	51	31	3	3. 36	3. 36	190
2, 035	50	29	3	3. 55	3. 58	210
1, 902	51	35	4	3. 57	3. 60	200
1, 869	50	32	3	3. 46	3. 50	190
1, 801	50	32	3	3. 34	3. 36	185
1, 774	51	31	3	3. 31	3. 35	153
1, 274	50	35	3	2. 40	2. 41	160
1, 459	50	35	3	2. 75	2. 75	185
1, 178	51	35	3	2. 23	2. 28	190
1, 234	51	35	3	2. 33	2. 26	180

** Obtained from the test samples cured in water at 20°C, 28 days.

the denser concrete combination in which sand was used as fine aggregates and magnetite which contains 52% of Iron elements was used as coarse aggregates. The experiment was carried out with varying w/c ratio. With the increase of w/c ratio, the workability improved whilst the volume density decreased. As shown in (A) of Figure 5, uniformity rose up to 10~20 %, i.e., heigher than that of ordinary concrete.

In mixing sand-magnetite which has an great difference in density (density difference 1.07), the w/c should be greater than that of ordinary concrete. Slump 3~4 cm seem to be adequate for this purpose. When the w/c ratio exceeds 55%, however, both the uniformity and density were decreased. Sample M-4 and M-5 are heavy concrete combinations with using magnetite powder (Fig 2, curve n) and magnetite coarse aggregate. In this case, S/A ratio was fixed and varied with the w/c ratio only. In the case of combination of aggregates with lower density difference (0.13), the uniformity drops as the w/c ratio increases. (see Fig. 5, (B)). M-6 is the case where magnetite (fine agg.) and magne-

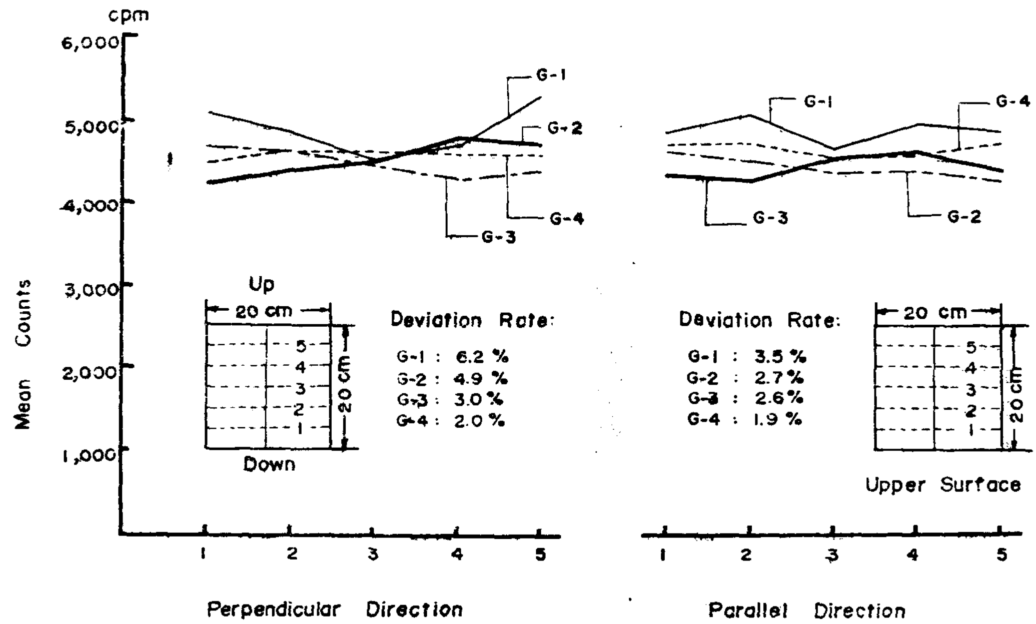

Fig. 4. Energent Fluxes of ^{60}Co-Gamma-ray through Granite Concretes

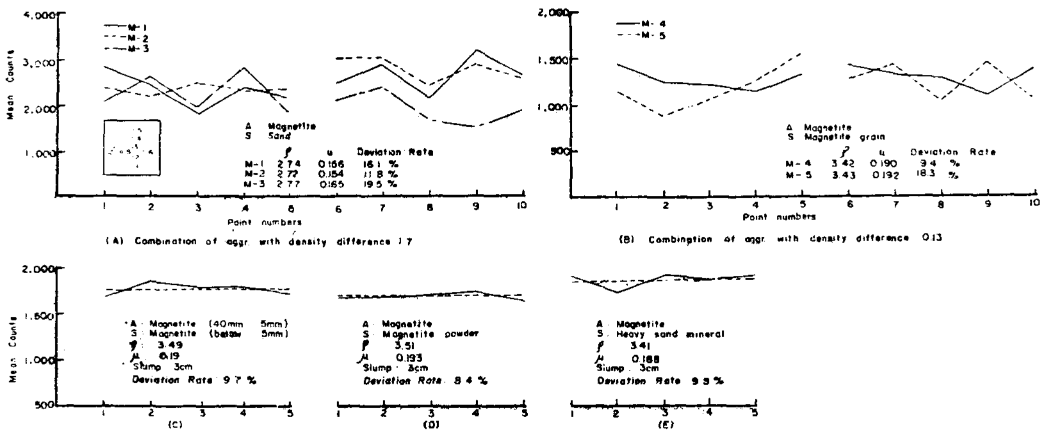

Fig. 5. Emergent Fluxes of ^{60}Co-Gamma-ray through Magnetite Concretes

tite (coarse agg.) have been used with having the grain curves of Fig. 2, k.b. It was able to get good one with uniformity below 10% deviation (Fig. 5, (C)).

If we raise up the mixing rate of coarse aggregate and use fine aggregate with high density, the density can be upgraded without loosing their workability. (See Table 3, M-7).

In T-3, P-1, H, the lead ore grain (Fe 25%, Pb 26%) was used as fine aggregate. The density of lead ore grain (4.3 g/cm^3) showed only a small difference from magnetite powder (4.1 g/cm^3). So did it from density of heavy concrete, products. However, due to Pb content in it, the costs of such concrete are considerably high.

Compressive strength of heavy concrete turned out to be sufficiently higher than that of ordinary concrete.

The water content in concrete evaporates up to 60~70% when the concrete gets completely dried up. These results approximately 0.1~0.2% reduction in specific gravity of heavy concretes.

4. Gamma-ray Transmission Experiment

In studying the shielding effect of the heavy concrete, gamma-ray transmission method was applied using 2 mCi of ^{60}Co point source and 2″ ϕ× 2″ NaI Scintillation detector associated with decade scaler (Model 181 A, Nuclear Chicago Co.).

Schematic diagram of experimental arrangement including collimator is shown in Fig. 6.

Concrete blocks of 20 x 20 x 20 cm^3 for investigation have been prepared and gamma-ray shielding effects tested using the transmission method. The tests were performed on five points of each concrete block, which is optionally taken, and therefrom statistical errors in experiments have been estimated.

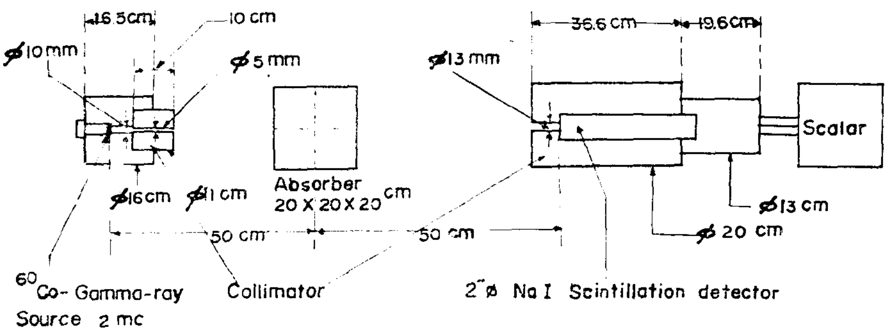

Fig. 6. Schematic Diagram for Apparatus and Collimating System

(a) Theory of gamma-ray transmission

On Fig. 6, for a narrow beam gamma-ray attenuation is expressed by the equation[3].

$$\frac{I}{I_o} = e^{-\mu x} \quad \cdots\cdots (1)$$

Where I_0 is the initial gamma-ray intensity (γ/cm^2 sec), I is intensity after passing through a thickness x of absorber (γ/cm^2 sec), x is absorber thickness (cm) and μ is linear absorption coefficient (cm^{-1}).

From the equation (1), the subdued length $(X)_{\frac{1}{e}}$ is defined as the thickness of absorber which will result in a reduction factor of $\frac{1}{e}$ in the initial beam intensity I_0, that is

$$(X)_{\frac{1}{e}} = \frac{1}{\mu} \quad \cdots\cdots (2)$$

A half value layer of absorber, $(X)_{\frac{1}{2}}$, defined as $I = \frac{1}{2} I_o$, and then it is given by

$$(X)_{\frac{1}{2}} = \frac{0.693}{\mu} \quad \cdots\cdots (3)$$

A tenth value layer, $(X)_{\frac{1}{10}}$, which is defined as $I = \frac{1}{10} I_0$ is formed from the above equation (Eq. 1)

$$(X)_{\frac{1}{10}} = \frac{2.303}{\mu} \quad \cdots\cdots (4)$$

5. Analysis of the Various Concrete Shields from the Economical Point.

From the practical point of application, it is of the most importance to choose the shield material which has low cost but is effective for radiation shielding. It is not easy, however, to find such a suitable material. A procedure of choosing the most promising material among those which are domestically available will be thus discussed here by experimentally searching for the relation between the shielding effectiveness and the material cost.

Since the biological shield-thickness is one of the important factors capable of determining the cost. a brief discussion on the shield-thick-

Table. 4. Summary of the Gamma-ray Transmission Experiment.

Aggregates		Trans-mission Ratio (10^{-2})	Linear Absorption Coefficient μ (cm^{-1})	Subdued Length (1/e-value) (cm)	Half-Value Length (cm)	1/10-Value Length (cm)	Mass Absorption Coeff. μm (cm^2/g)	Measured Density (g/cm^3)
Fine	Coarse							
Mag. fine grain	Magnetite	2.09	0.193	5.2	3.6	11.9	0.0555	3.51
Mag. fine grain	Magnetite	2.26	0.190	5.3	3.6	12.1	0.0557	3.45
Heavy sand mineral	Magnetite	2.34	0.188	5.3	3.7	12.2	0.0551	3.41
Mag. fine grain	Magnetite	2.16	0.192	5.2	3.6	12.0	0.0560	3.43
Mag. fine grain	Magnetite	2.32	0.188	5.3	3.7	12.2	0.0551	3.41
Lead Ore	Magnetite	1.92	0.198	5.1	3.5	11.6	0.0553	3.58
fine grain	Lead Ore	1.84	0.200	5.0	3.5	11.5	0.0556	3.60
Mag. fine grain	Lead Ore	1.98	0.196	5.1	3.5	11.8	0.0560	3.50
Hem. fine grain	Hematite	2.43	0.186	5.4	3.8	12.4	0.0550	3.38
Mag. fine grain	Magnetite	2.48	0.185	5.4	3.7	12.4	0.0552	3.35
Sand	Magnetite	3.73	0.165	6.1	4.2	14.0	0.0595	2.77
Mag. fine grain	Slag	4.37	0.157	6.4	4.4	14.7	0.0569	2.76
Sand	Granite	7.89	0.127	7.9	5.5	18.1	0.0562	2.26
Sand	Tun. Ore	7.74	0.128	7.8	5.4	18.0	0.0566	2.26
Sand	Silver Ore.	7.47	0.130	7.7	5.3	17.7	0.0570	2.28
Sand	Gravel	7.26	0.131	7.6	5.3	17.6	0.0565	2.32

ness will be made prior to analyzing the economical factor of the shielding materials.

5.1 Determination of Biological Shield-thickness.

Biological shield-thickness is defined as the thickness of material required for which the emergent radiation flux does not exceed that corresponding to the maximum permissible dose for the human body. Biological shield-thickness depends on the shielding structure, radiation characteristics in question, shielding material and others. For convenience' sake, radiation source which is surrounded by cylindrical shield is assumed in this study. Although an economical factor is always emphasized, heat resistant problem of the shielding structure must be take into account in designing the biological shield for large radiation source.

Energy loss of radiation in medium results in a temperature rise of the material. Since the temperature increase is in part related to radiation flux, the biological shield should be designed under consideration of this problem.

Lane[4] obtained that the maximum tolerable heat flux on the inside surface of the biological shield is about 100 Btu/hr/ft^2 by using conservative values for the thermal conductivity and thermal stress limitations for concrete shields. This gives a temperature rise of about 10°C in the shield. The radiation intensity corresponding to this heat flux is about 2 x 10^{11} Mev/cm^2/sec. If this flux is calculated with regard to the ^{60}Co source from which 1.17 and 1.33 Mev gamma-ray are emitted, the ^{60}Co gamma-ray flux will be 8 x 10 $^{10}\gamma$/cm^2/sec. In order to reduce this gamma-ray flux to the maximum permissible level of 2.5 mRem/hr. which is equivalent to 1250 Mev/cm^2/sec, the biological shield-thickness in which an attenuation factor of at least 1.8×10^8 can be obtained is necessary.

Reduction of radiation intensity depends upon source geometry, shield material and so on. Valuable formulae are found in Reactor Shielding Manual[5] for calculating the shield-thickness for various source-and-shield geo-

Table 5. Estimation of the Costs for Biological Shield.

Aggregates	Linear Absorption Coefficient μ (cm^{-1})	Specific Gravity (g/cm^3)	Biological Shield Thickness (cm)	Unit Costs of Concrete (10^2Won/m^3) **	Biological Shield Cost for Reactor Core of Diameter 3m (10^3Won)	Diameter 6m (10^4Won)	Diameter 12m (10^4Won)
Magnetite (Po-chun mine)	0. 156	2. 74	119. 4	67	314	108	395
	0. 190	3. 42	97. 6	124	469	160	596
	0. 192	3. 43	96. 4	120	431	152	564
	0. 190	3. 49	97. 6	122	458	157	585
	0. 193	3. 51	96. 4	126	464	159	592
	0. 188	3. 41	98. 7	380	1. 433	496	1, 843
Magnetite (Mul-kum mine)	0. 188	3. 41	98. 7	125	466	163	607
	0. 185	3. 36	100. 0	124	480	164	608
	0. 198	3. 58	94. 1	312	1 '117	383	1, 43o
Hematite (Chung-ju mine)	0. 186	3. 38	100. 0	364	1, 406	480	1, 781
Lead Ore (Woll-am mine)	0. 200	3. 60	93. 0	869	3, 070	1, 055	3, 937
	0. 196	3. 50	95. 2	300	1, 090	374	1, 392
Magnetite (Kyung-in mine)	0. 185	3. 35	100. 0	131	508	174	684
Slag from (Chang-hang)	0. 137	2. 41	135. 6	35	199	66	238
	0. 157	2. 76	117. 6	72	340	115	423
Tun. Ore (Sang-dong mine)	0. 186	2. 26	145. 5	45	280	92	333
Granite (Mt. Bul-am)	0. 123	2. 20	150. 9	20	131	43	155
Gravel (Han River)	0. 127	2. 25	145. 5	21	128	43	156
	0. 131	2. 32	142. 9	31	189	64	231
Silver Ore (Si-hung mine)	0. 130	2. 28	142. 8	21	130	42	153

** Estimated from Table 3. Processing and installation Charges are not included.

metries. In the case of practical shielding calculation, above mentioned every possible factors must be taken into account. However, for the first approximation, it is assumed that the build-up factor and geometrical factor may be compensated for one another. With this assumption, we used the equation (1) for the calculation of biological shield-thickness.

The biological shield-thickness, $X_{b,s}$, will be

$$X_{b,s} = \frac{l_n\ 6.25\times 10^{-9}}{\mu} = \frac{18{,}891}{\mu} \quad \cdots\cdots\cdots\cdots (5)$$

5.2 Economical Analysis of Various Concrete Shields.

The linear absorption coefficients, specific gravities, biological shield-thickness of concrete necessary for an attenuation factor of 1.8×10^8 and biological shield cost for the different sizes of nuclear reactor core are given in Table 5.

The biological shield-thickness for the materials of interest was calculated from Eq. (5) and Tables 2 and 3. Unit cost for each material of 1 m^3 were estimated from market surverying of the cost of aggregates and cement. For conveience of comparison, consider the biological shields of reactor cores which are consisted of a cylinder with different diameters, that is 3 m, 6 m, and 12 m. Calculations of the biological shield cost for each size core were based on an appropriate shield with thickness and unit cost as given in Table 5. In these calculated costs, those for additional thermal shield are included. As might be expected, the heavy aggregated concretes have absorption coefficietns larger than those for ordinary concretes. This decreases the biological shield size. As can be seen in Table 5, the biological shield-thickness is decreased as thick as about 50 cm by the former compared to the latter. If the heavy-aggregated concretes are used in designing the biological shield for the reactor size of 3 m, 6 m, 12 m diameters, the extra useful space area compared to those that may be occupied by the ordinary concrete is obtained as large as 8.6 m^2 13.3 m^2 and 22.8 m^2 for each reactor size, respectively. A graph of the specific gravities against the biological shield cost for gamma-radiation is shown in Fig. 7.

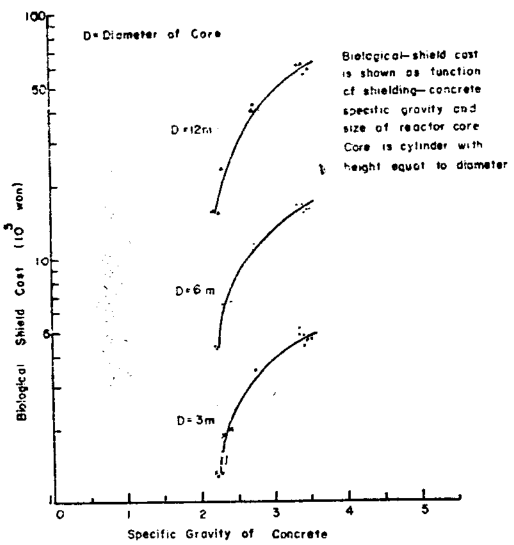

Fig. 7. Estimation of Biological Shield Cost Vs. Specific gravities of Concrete

Figure 7 shows that a concrete with the specific gravity of 3.4~3.5 g/cm^3 may be a promising material for the biological shield. Summary up the above, it may be drawn as a conclusion that magnetite produced in Pochun or in Mulkum mines is the most promising material for the biological radiation shield.

6. Shielding Effect of Heavy Concrete

Shielding effects for various concretes have been investigated by the use of gamma-ray transmission method. Table 4 present transmission ratios, linear absorption coefficients, $\frac{1}{e}$ values which are called the subdued lengths, half-value lengths, $(X)_{\frac{1}{2}}$, $\frac{1}{10}$ value lengths, absorption coefficients together with the measured densities for various concretes.

As might be expected, the gamma-ray transmission rates increased with decreasing densities of concretes. For various concretes under investigation, the following relation between gamma-ray transmission rates and concrete densities was shown as the combinations of (lead ore, lead ore) $<$ (lead ore, magentite) $<$(magnetite, magnetite,) $<$ (heavy sand, magnetite) $<$ (magnetite, slag) $<$ (sand, granite). In the above parenthese, former represent fine aggregates and latter represent coarse aggregates of concrete combinations. Comparing these with regard to the gamma-ray shielding effects, it is just an opposite against the above relation. Therefrom, it may be clearly stated that there is a close relationship between material density and gamma-ray absorption coefficient[3].

From data in Table 4, we can derive an empirical formula governing the relation between density of concrete and linear absorption coefficient. By a least squares fitting, it forms for the concretes with a density smaller than 7.8 g/cm^3.

$$\mu = 0.0532\ \rho + 0.0083 \cdots\cdots\cdots\cdots\cdots\cdots (6)$$

where μ is the linear absorption coefficient and ρ is the density of concrete. In Eq. (8) a constant of 0.0083 is the linear absorption factor for an thickness of 100 cm which is equal to the radiation source-to-detector distance.

7. Conclusion

Various heavy concretes have been manufactured using the domestically produced-minearal ores and-cements. Radiation shielding effects for them have been investigated by means of gamma-ray transmission method. The economic problem of concretes manufactured for biological shield of radiation has been also intensively studied in the standpoint of practical application. From these studies as mentioned above, some conclusions may be drawn as follows.

1). Magnetite seems to be the most promising aggreagte material among mineral ores used in this study because magnetite has a relatively high density of 4.25 g/cm^3 in average, a good physical strength as well as economical and readily avialable in domestic market. A concrete in density of about 3.4 g/cm^3 with a good physical strength has been obtained by mixing up coarse aggregate of magnetite with magnetite fine aggregate of about 54% iron elements.

2). It seemed that the concrete density and workability are greatly influenced by grain size in making the concrete. The best conditions of obtaining a good homogeneous concrete in the same content material seemed to be 50～52% of w/c ratio and, about 3 cm in slump, coarse aggregate of about 60% with a grain size of 20～40 mm. In the case of heavy concrete compared to the ordinary concrete, its uniformity was deteriorated above 3 cm in slump because of separation tendency of composite material.

3). In order to enhance the workability and homogeneity of concrete, powder with a grain size of about 0.6 mm or less whose density is higher than that for coarse aggregate should be taken if magnetite is essentially used for making the heavy concrete.

4). An empirical expression between the overall density of shield concrete and the linear absorption coefficient of ^{60}Co gamma-ray was experimentally obtained as

$$\mu = 0.0532\ \rho + 0.0083$$

5). Magnetite which is now produced in Pochun and Mulkum mines seems to be the most promising aggregate for economically making the heavy concrete with a good shield effect of radiation.

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