HEAVY WEIGHT CONCRETES FOR RADIATION SHIELDING

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INTRODUCTION

The advent of the nuclear power industry creates a great demand for concrete these days. The vast usage and production of penetrating radiation due to the use of nuclear reactors, particle accelerators, industrial radiography, and x- and gamma-ray therapy entails the use of shielding material for human protection against biological side effects. Both normal and heavy weight concretes are good, versatile and economical materials for shielding purposes.

It is the main purpose of this paper to discuss different aspects of concretes used for shielding purposes.

Factors Involved in Radiation Shielding

The first purpose of radiation shielding is to reduce the intensity of the radiation to the acceptable level. Secondary to this are economic and mechanical factors, which are interrelated. Reducing the radiation level is relatively simple. Almost any material serves as radiation shielding if thickness is sufficient. Although water is a good neutron shield, a very thick layer of it is needed for this purpose. Besides, there is the danger of water tanks leaking. On the other hand, lead shields are very effective against gamma radiation but do not provide sufficient mechanical strength, especially for large, permanent shielding structures.

Fortunately, concrete is a very suitable shielding material for large, permanent shields. It has good compromise thickness requirements for both neutron and gamma-ray attenuation. It also provides sufficient mechanical strength and is reasonable in cost. Ordinary concretes provide a good shield with enough thickness, but heavy concrete provide the same amount of shielding with less thickness. Instead, the unit cost is higher for the heavy concretes. Certain mechanical problems such as homogeneity are common to both types. Assuming that mechanical requirements are met, the space requirements and economics of the project will guide the constructor to the type of concrete.

Homogeneity

Homogeneity of concrete used in shield construction is very important, since otherwise the thickness requirement of design is not met in some parts. Such portions may prove inadequate due to the degree of seriousness. A radiation shield is as good as its weakest point. If segregation occurs or air pockets are introduced into the mixture, the effective thickness is reduced and this magnifies the intensity of radiation.

Mechanical Problems

The construction of concrete shields involves some mechanical problems. Since there are many pipelines involved and these pipes are rather scattered, sound thought should be given to the formwork for fitness of these pipes. Because of the complicated formwork, skillfull and accurate placement of concrete is necessary to avoid segregation. Additional thicknesses and special plugs are necessary in place of these pipe passages. For heavy concrete, form pressures are greater, and the shrinkage is more seriuous due to high water content. So, in order to prevent cracking and segregation, great care must be taken. On those occasions when scrap iron is used as aggregate, it is logical to investigate the workability[1] of concrete to insure proper placement and consolidation.

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[1] The composite quality sought, involving ease of placement and resistance to segregation is termed "workability." (See Composition and Properties of Concrete, by Troxell, Davis, and Kelly, p. 108.)

Economics of Shielding

Due to the great differences between heavy and ordinary concretes, cost factor should be observed. Heavy concretes are higher in cost due to the higher freight cost of aggregates, higher cost of special aggregates themselves, and unfamiliarity of contractors to their properties.

A 7.7 ft thickness of magnetite concrete will approximately provide a shielding efficiency equal to a 10 ft width of ordinary concrete. Cost studies must be done to compare both concretes in any project. However, in different occasions and locations it will bring different results.

Mechanics of Shielding

Here we will consider the absorption of gamma rays and neutrons. Both of these could be absorbed by a barrier. Two different categories happen with regard to radiation, i.e., when the source of radiation is a point more or less, the geometry is considered as spherical; and when the source is considered as a plane on one side or a wall with its intensity measured at the other side, the geometry is called plane. These geometries are explained in Figure 1. The two common formulas for calculation of absorption for these two geometries are:

$$\text{Spherical:} \quad I = I_o \left(\frac{1}{a + x}\right)^2 e^{-\mu x} \tag{1}$$

$$\text{Plane:} \quad I = I_o e^{-\mu x} \tag{2}$$

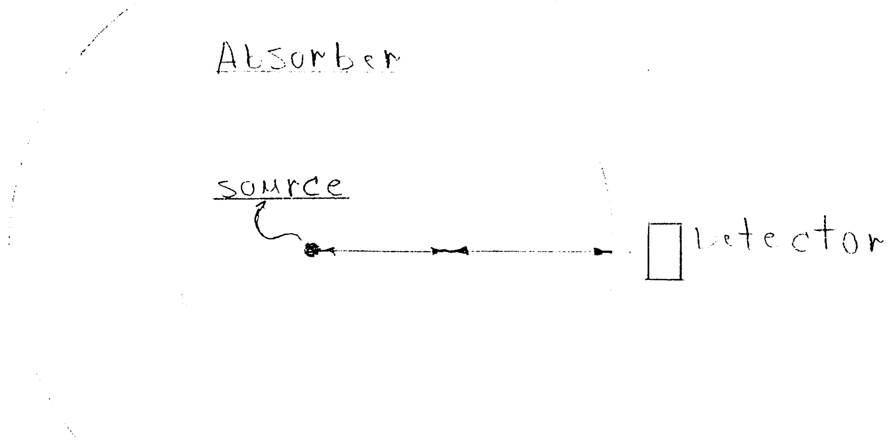
where

I = intensity of radiation at point x (Figure 1);

I_o = intensity of source;

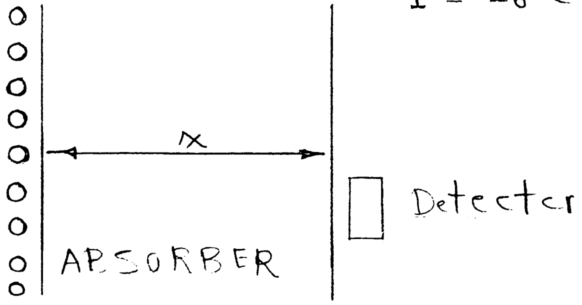
μ = absorption coefficient of the barrier material;

$$I = I_0 \left(\frac{1}{a+x}\right)^2 e^{-\mu x}$$



Global or Spherical Geometry

$$I = I_0 e^{-\mu x}$$



Plane Geometry

Fig. 1 - Geometry Types used For Absorption Measurment, courtesy of Journal of The American Concrete Institute, Sept. 1953

x = thickness of barrier; and

a = distance from source to the first point of barrier.

The factor $1/(a+x)^2$ in Equation (1) is to reduce the intensity of radiation due to the distance, such as for light and/or gravity. When the distances from the source is large or thinny barriers are to be used, Equation (2) may be used. Intensity of flux is measured in terms of r per hour, m rem per hour, neutron flux, or similar units. The term $e^{-\mu x}$ gives proper reduction of intensity due to the thickness x of barrier material.

Half-Thickness

The thickness of an absorber to reduce the intensity of the source by one-half is called half-thickness and introduced in inches or centimeters. It is calculated by means of the formula below:

$$T \frac{1}{2} = 0.693/\mu \qquad (3)$$

where T 1/2 is the half-thickness, and μ is the absorption coefficient. Half-thickness is a function of the intensity of our source and the thickness of the barrier. Another factor which is sometimes used instead of half-thickness is relaxation length. Relaxation length, which is equal to $1/\mu$, is a length of absorber to reduce the intensity of the source by 63.2 percent instead of 50. However, the use of half-thickness is more common and the number of half thicknesses to reduce the intensity to the specified limit may be calculated by means of Equation (4):

$$N = 3.322 \log R \qquad (4)$$

where N is the number of half-thicknesses required to reduce the intensity by a factor of $\underline{R}$, which is called reduction factor. The reduction factor is computed by dividing the source intensity by the desired intensity outside the shielding.

Radiation Source Power

In the case of the gamma-ray, its emitting power or strength is described with a unit called curies. A curie, c, is the certain amount of radioactive isotope which has 3.7×10^{10} separations per sec. If dealing with a point source of emission, the intensity of source may be found from Equation (5):

$$I_o = 7c \frac{E}{a^2} . \tag{5}$$

where

I_o = intensity of r/hr at one ft from the source;

c = number of curies of the isotope;

E = energy of emitted γ-rays in mev/separation of atom; and

a = distance from the source to the inside wall of the shield, ft.

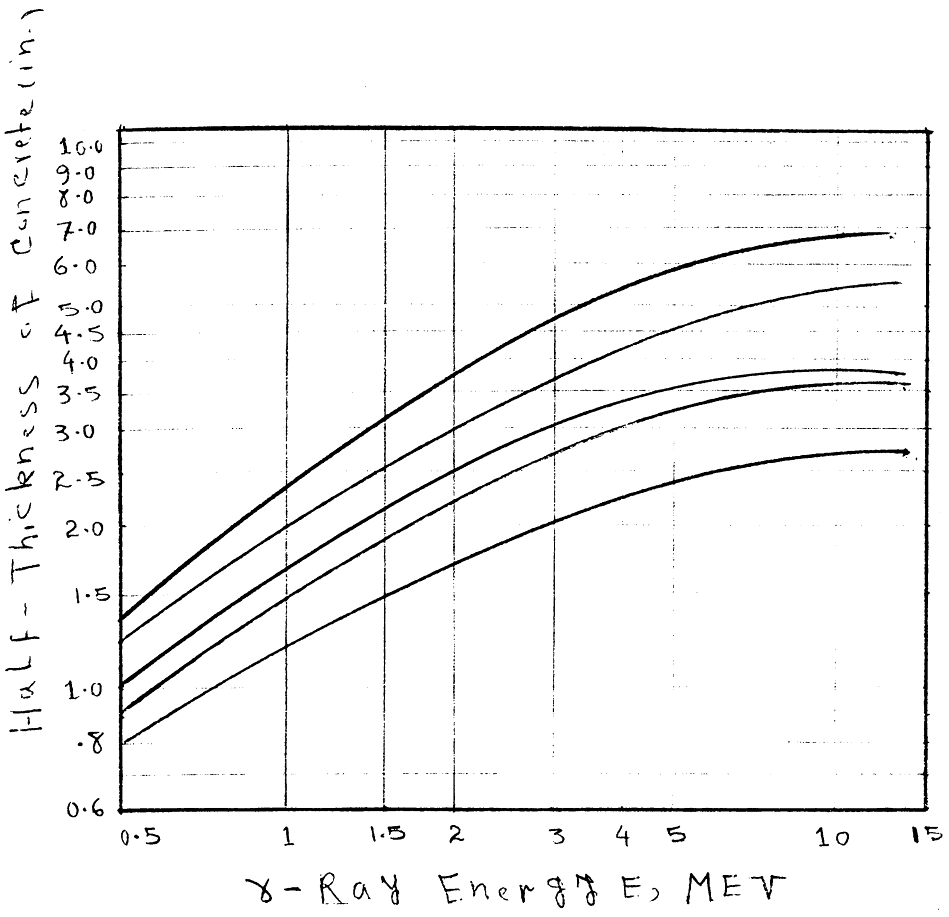
Both N and γ rays could be considered the same or similar in effect for the purpose of this paper. The unit of gamma radiation is known as roentgen (r) and is the quantity of a radiation which produces 1.6×10^{12} ion-pairs in one gram of dry air at standard conditions. A dose of 700 r is considered fatal to the receiver while a 200 r will make the recipient sick with 50 percent probability.

There are other units used commonly in design criteria which are originated from basic roentgen. For example, the roentgen-equivalent-physical (rep), which is the amount of radiation to produce an energy absorption of 83 ergs per gram in air. Another commonly used unit is the roentgen-equivalent-man, rem, which is the radiation quantity to cause the same biological effects as a roentgen of γ-radiation. These two explained units, rep and rem, are used for other sources of radiation as well as for γ-radiation. For example, rem, the roentgen-equivalent-man, is the amount of any radiation which will cause the same biological effect as a roentgen of γ-radiation. Neutron radiation, on the other hand, is described in terms of neutron flux, which is the number of neutrons crossing an area of one cm^2 in one second ($n/cm^2/sec$). Neutrons are more hazardous biologically than are gamma emissions. For this reason, shielding against the gamma-ray is much easier than against neutrons. Figure 2 contains the half-thickness values for both ordinary and heavy concretes. Table I provides information about shield thickness and half-thickness for different degrees of reduction and different gamma source powers. It is recommended that at the occasions when Figure 2 is being used for determination of half-thickness at emission ranges of more than 5 mev, one or two half-thicknesses must be added to whatever thickness which curve recommends.

As shown in Figure 2, the half-thickness value increases with γ-ray energy up to 15 mev level or so where it starts to get level. Beyond the energy level of 15 mev, the value of half-thickness decreases due to a phenomenon known as pair-production on γ-ray. The effect gets more obvious in the case of using heavy weight concretes.

Shielding Against Neutron Particles

In the case of neutrons, changes in water content as well as presence of special elements like boron could cause drastic effects on the value of half-thickness in thermal neutron's case. However, for faster neutrons this is not the case, since their range of resonance is above ranges of resonance capture of materials used in shielding ordinarily. Therefore, the half-thickness will increase regularly with the increase of energy levels. In Table II there is some information about the half-thicknesses suitable for different kinds of concrete and energy levels. In the case of using special elements like



Type of concrete	Legend	
	Sign of concrete	Density gr/cm^3
Plain	×	2.2 — 2.4
Limonite	×	2.6
Limonite + scrap FE + pyrex	×	3.6
Magnetite or Barite	×	3.0 – 3.8
Limonite + scrap FE	×	4.4

Fig. 2 — Half Thickness Values As a function Of γ-radiation Strength and Different concretes*

Reduction Factor		2		10		100		1000		10^6	
Energy of γ-ray	Type of concrete	S.T.* in.	$T_{1/2}$ in.	S.T in.	$T_{1/2}$ in.	S.T in.	$T_{1/2}$ in.	S.T in.	$T_{1/2}$ in.	S.T in.	$T_{1/2}$ in.
1 Mev	Plain	3.2	3.19	9.3	2.8	17.1	2.57	24.5	2.46	45.6	2.29
1 Mev	Magnetite	2.0	1.98	5.8	1.73	10.6	1.6	15.3	1.53	28.3	1.42
1 Mev	Limonite	2.8	2.82	8.2	2.47	15.1	2.27	21.6	2.17	40.3	2.02
1 Mev	Limonite + Iron	1.7	1.72	5.0	1.51	9.20	1.39	13.1	1.31	24.3	1.22
1 Mev	Limonite + Iron + Pyrex	2.1	2.10	6.1	1.83	11.20	1.69	16.2	1.62	29.9	1.50
3 Mev	Plain	5.3	5.27	15.9	4.78	29.8	4.48	42.9	4.30	81.1	4.07
3 Mev	Magnetite	3.1	3.07	9.4	2.82	17.5	2.64	25.4	2.55	48.0	2.41
3 Mev	Limonite	4.7	4.69	13.6	4.10	25.5	3.84	36.9	3.70	69.8	3.50
3 Mev	Limonite + Iron	2.6	2.59	7.9	2.39	15.0	2.25	21.5	2.16	40.9	2.05
3 Mev	Limonite + Iron + Pyrex	3.2	3.2	9.8	2.94	18.4	2.77	26.5	2.66	50.2	2.52
5 Mev	Plain	6.8	6.81	20.9	6.30	39.8	5.99	57.9	5.81	110.0	5.52
5 Mev	Magnetite	3.5	3.52	11.1	3.34	21.4	3.22	31.3	3.14	59.6	2.99
5 Mev	limonite	5.4	5.43	16.9	5.08	32.4	4.87	47.3	4.74	89.9	4.51
5 Mev	Limonite + Iron	2.8	2.84	9.0	2.71	17.4	2.62	25.6	2.57	48.8	2.45
5 Mev	Limonite + Iron + Pyrex	3.6	3.57	11.30	3.41	21.9	3.29	32.0	3.21	61.2	3.07

Table 1- Required thickness for shields, S.T., and half thicknesses, $T_{1/2}$, for different concretes and reduction factors and various gamma-ray energy levels, courtesy of ACI publication, 1953

Type of concrete	water content g/g of conc	Neutron Energy	Geometry	Half-Thickness (in.)
Ordinary	—	0.85 Mev	Spherical	3.9
Magnetite	0.112	0.85 Mev	Spherical	2.9
Ordinary	0.076	18.8-4.5 Mev	plane	3.9
Ordinary	0.076	thermal	Plane	3.6
Ordinary	0.05-0.1	thermal	Spherical	5.6
Ordinary	0.05-0.1	thermal	Plane	4.1
Ordinary	—	90 Mev	Plane	9.5
Barite	—	90 Mev	plane	9.5
Ordinary	—	280 Mev	Plane	18.0
Ordinary	0.084	thermal	Plane	4.19
Ordinary	0.084	15-50 ev	plane	3.1
Magnetite	0.055	thermal	Plane	3.3
Magnetite	0.055	15-50 ev	Plane	2.5
ordinary+Pyrex	0.059	thermal	Plane	2.90
ordinary+Pyrex	0.059	15-50 ev	Plane	2.70
Limonite	0.186	thermal	Plane	1.90
Limonite	0.186	15-50 ev	Plane	1.70
Limonite+Iron	0.079	thermal	Plane	2.10
Limonite+Iron	0.079	15-50 ev	Plane	1.9
Limonite+Iron + Pyrex	0.128	thermal	Plane	2.0
"	0.128	15-35 ev	Plane	1.9
"	0.128	35-50 ev	Plane	1.9

Table 2 - Half Thicknesses Required For Different Concretes and Different Neutron Energy Levels

cadmium or boron, special care must be taken about detrimental effects of these elements. In cases when boron additives are used in mixes, all of the fines passing a No. 30 sieve is usually eliminated. This has some positive effects on the mix, since it reduces the surface area of the mix and so reduces its reactivity with boron. On the other hand, coarser mixes have the deficiency of not letting boron spread uniformly all over the mix, and this lessens the good effect of boron or cadium in capturing neutrons. Ordinarily, addition of boron and cadmium delays the time of setting of concrete considerably, but addition of one pound of calcium chloride per hundred pounds of cement overcomes this detrimental effect completely. By looking at Table II, it is obvious that an increase in water content reduces the half-thickness of the shield in the case of thermal neutrons. But there is still a lot of questions about the effect of adding iron and pyrex to the concretes as such an action may overcome the effect of water content in half-thickness criteria. More tests should be run with this regard. From the curve of Figure 3, it is obvious that the half-thickness will increase with increasing neutron energy. In the low energy regions ($E < 30$ mev) where resonance absorption of some elements might reduce the half-thickness drastically, the drawn curve is not accurate, since there has been no investigation about the effect of such additive materials. However, the curve is on the conservative side, fortunately.

Highlights in Shielding Design

In order to be able to design a shield, we have to know the energy level of different isotopes. Table III contains useful information regarding the most commonly used isotopes. Use of Equation (5) lets the engineer know the intensity of the source he is dealing with. In the case of some of the

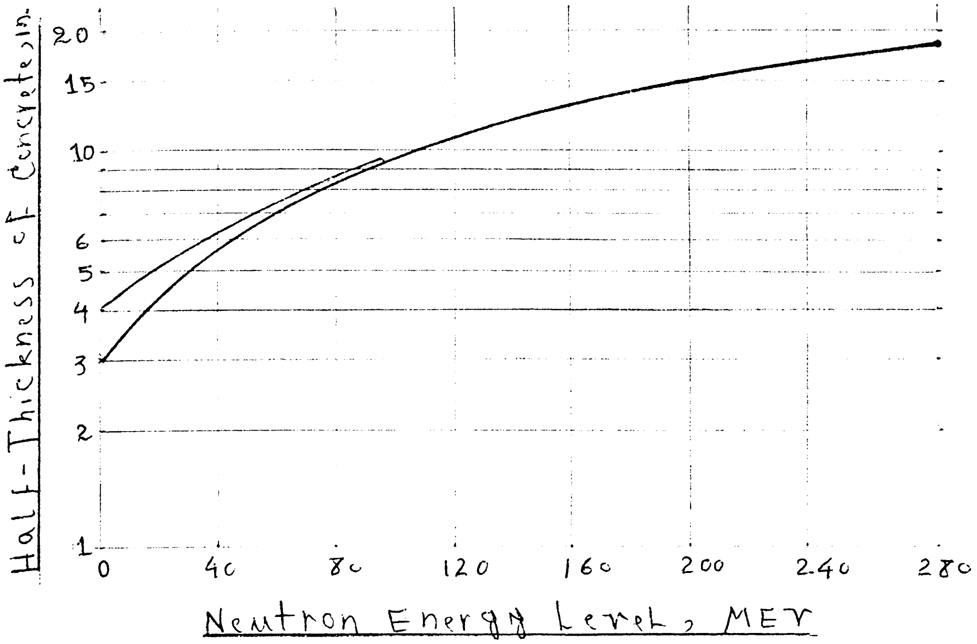


Fig. 3 - Relation Between Neutron Energy Level and Half-Thickness of concrete

Courtesy of ACI, Sept. 1953

Isotope	Energy of radiation, Mev	Remarks
C^{14}	—	β-radiation only
Na^{24}	1.38, 2.76	—
P^{32}	—	β radiation only
Co^{60}	1.17, 1.33	—
I^{131}	.638 (15%), .364 (79%), .238 (6%), .8 (6%)	—
Eu^{154}	1.12 max	Use 1.12 as E in Eq. 5
Ir^{192}	1.2 max	Use 1.6 as E in Eq. 5
Ra^{226}	0.188 (Ra only)	For sealed radium sources, the disintegration emits also γ rays of 2.42, 2.20, 2.09, 1.82 MeV and others as well.
Ra-Be	4.4 Avg., 12 max.	K = 16,000 n/sec./mc Ra in Eq. 6
Po-Be	4.1 Avg., 10 max.	K = 2,500 n/sec./mc po in Eq. 6
Low power reactor	Thermal Neutrons	$10^6 - 10^7$ n/cm²/sec.

Table 3 - Specifications of some popular gamma and neutron emitting isotopes

isotopes there is more than one energy level. The reason is that some isotopes have the ability of emitting two different energy levels. Suppose that the source to be used is two curie of Co^{60} (cobalt isotope with atomic weight of 60). Co^{60} emits γ-rays in two different energy levels of 1.17 and 1.3 mev, but both of these ranges are emitted equally, i.e., each of these share 50 percent of radiation. Using Equation (5) we get,

$$I_o = 7\ CE/a^2$$

$$I_o = 7 \times 2 \times (1.33 + 1.17)/(1)^2 = 35 \text{ r per hour at } a = 1 \text{ ft from source}$$

There are several tables which show the acceptable doses of radiation not harmful to health. Table IV is a sample of these tables. However, 0.00625 r/hr is the highly accepted intensity of radiation for γ-radiation; so, dividing the dose rate by standard tolerance reveals the reduction factor necessary. This reduction is to be done by shield,

$$\text{Reduction Factor} = \frac{35}{.00625} = 5600$$

Now we can compute the number of half-thicknesses necessary by means of Equation (4):

$$N = 3.322 \log R = 3.322 \log 5600 = 12.45 \text{ half-thickness}$$

In some instances the isotope emits different energy levels with different contributing percentages. Isotope I_{131} is one of these types. When this isotope disintegrates, it yields a 0.638-mev γ-radiation in 15 percent of disintegrations, a 0.364-mev gamma-rays in 79 percent, and 0.284 and 0.080 mev radiations in 6 percent of disintegrations. Supposing a source consisting of two curies of this isotope, we compute the intensity of radiation simply by averaging among the energy values,

$$I_o = 7c\ E/a^2 \qquad a = 1 \text{ ft}$$

Type of radiation	mrem per week	mrep per week	mrem per day	Flux, in n per sq. cm sec, giving 60 mrem per 24 hrs.
x- or γ-rays	300	300	60	
Fast Neutrons	300	30	60	$20/(1.2\ e^{-E/2})^{*}$
Thermal Neutrons	300	60	60	600

E is neutron energy in Mev

Table 4- Maximmun allowable exposures to radiation

$$I_o = 7 \times 2 \times [(0.638 \times .15) + (0.364 \times .79) + (.284 + .08) \times .06]/1$$
$$= 5.67 \text{ r/hr.}$$

For neutron isotopes the source strength is usually designated in units like number of neutrons per sec-mc of isotope where mc stands for milli curi of isotope. The neutron flux can be calculated by means of Equation (6) for a certain distance off the source,

$$I = 8.57 \times 10^{-5} KM/a^2 \tag{6}$$

where

I = neutron flux, n/5 g cm/sec;

K = a constant depending on the kind of isotope given in Table III;

M = number of millicuries of active isotope; and

a = distance from the source.

Then, for a radium isotope source of 500 mc of Ra content with K = 16,000 n/sec/mc Ra, the flux at 2 ft from the source would be

$$I = 8.57 \times 10^{-5} \times 16000 \times 500/(2)^2 = 171.4 \text{ n/cm}^2\text{/sec.}$$

Mev, which stands for million electron volts and was frequently used in past pages, is the unit for energy of radiation and is the amount of energy which would be acquired by an electron in falling through a potential of 1,000,000 volts. It is also equal to 1.6×10^{-13} watt-sec. As an indication for this unit, an ordinary TNT explosion releases about 10 ev per molecule, while about 200 mev are released by a fissioned atom.

Procedure for Design of Simple Radiation Shielding

Although design of radiation shielding and similar structures is a difficult task due to the inherent hazards of the industry, a crude estimate could be made about the cost of shielding with either plane or heavy weight concretes by means of which a decision might be made about the type of concrete to be used. The above mentioned procedure consists of several steps as follow:

1. The type of source and radiation involved should be determined.

2. Using the source intensity and taking tolerances from proper tables, find out the reduction factor, R.

3. With the use of half-thicknesses for different types of concrete, find out the shield thickness in either case.

4. Knowing the reactor volume and shield thickness, determine the floor areas and volumes.

5. From the shield sketches, find out the weak points and add thickness there.

6. Prepare an approximate cost estimate including cost of formwork, concrete and its placing for different types of concrete.

7. Knowing the differences in dimensions due to the use of different concretes, determine the savings due to the use of a certain one.

8. If no design criteria are neglected, use the most economical concrete on the basis of economics.

However, the dense concretes are the main subject to be discussed in this paper. Structural requirements of concrete shields are quite low due to the thickness of the shields. Overall, the major stresses and strains are due to the thermal stresses which in turn are due to the high temperatures inside the shield. Dense mixes proportioned on a volumetric basis are expected to have the same structural properties as the mix made with ordinary aggregates. Whenever a very hard aggregate such as magnetite iron ore is used, the strength increases since aggregates are the main load-carrying agents in any concrete. Specific heat and thermal conductivity of concretes are very important wherever thermal stress problems are to be considered. These properties are nearly identical in magnetite and ordinary concrete. However, they are considerably lower for barite concretes and higher for those which contain metallic aggregates.

Workability is much poorer in the case of heavy concretes than in the case of ordinary concretes. Several factors cause this problem. For example, when crushing dense aggregates, they turn to more sharp, angular and elongated particles and this causes poor workable mixes. Also, in order to increase the density there must be a reduction of air-entraining agents, cement and free water which all contribute in proper workability of mixes. Another reason is the dense materials themselves which of course need more effort to move.

There are several types of heavy concrete mixes used in construction these days and each of these has its own advantages and disadvantages. For the rest of this paper, iron-serpentine concrete and heavy steel-aggregate concrete will be discussed.

IRON-SERPENTINE CONCRETE

Nature of the Concrete

Iron-serpentine concrete is considered a heavy weight concrete applicable for shielding purposes in which iron provides the high density for slowing down the radioactive particles,and crushed serpentine rock and portland cement provide the concrete with high attenuative values against neutron particles due to their chemically bound water. Formerly, hydrous-iron ores such as limonite were used, but the fact that limonites could not be used in the inlets and outlets of the shield (neutron production reactor) where operating temperatures of 300°C and above drive off most of its bound water necessitated replacing it by another filler. The serpentine aggregate can hold its bound water to the temperatures as high as 450°C; thus it could be used as an ideal aggregate. Also, large deposits of serpentine make its use more objectionable. Figure 1 provides some useful information about temperature resistance of different aggregates in addition to serpentine. Concretes made with serpentine aggregates alone weigh from 100 to 150 pcf, depending on the type of serpentine used. Such a concrete will have more water than necessary for neutron attenuation. Therefore, it is possible to replace part of serpentine with a type of heavy aggregate such as magnetite or steel slugs without defecting the useful role of bound water in neutron attenuation and decreasing the shield thickness considerably. On the other hand, some types of serpentines are soft, friable, and impure. Most of the time the main impurity consists of a mineral called chrysotile. Although chrysotile is of the same mineral formula as serpentine, it is the fibrous form of it and is called asbestos.

The PA (preplaced aggregate) concreting method which is used when using

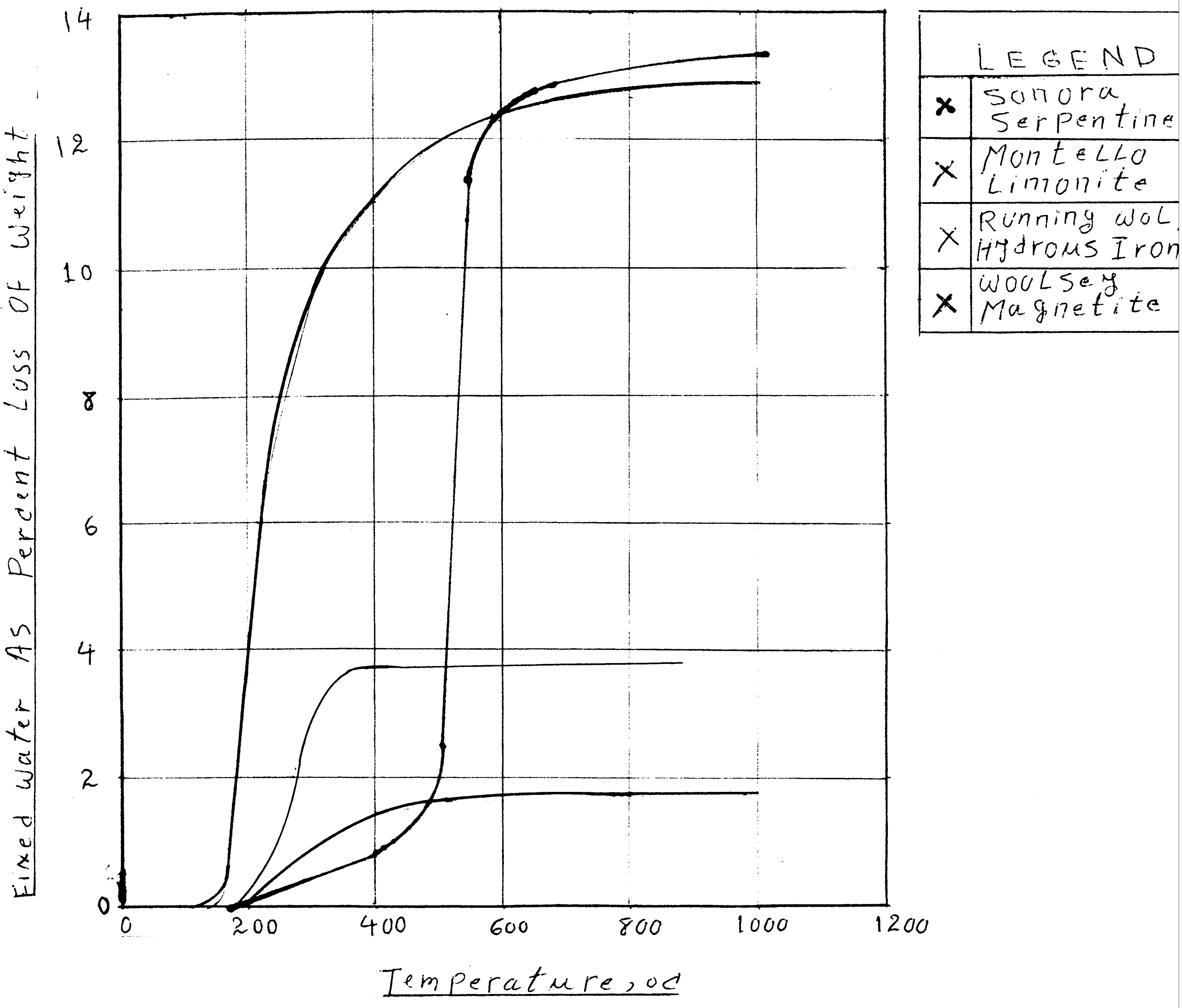


Fig. 1 - Water Retension Of Different Hydrous Aggregates

courtesy of American Concrete Institute, Special Publicat serpentine aggregates requires premixture of coarse serpentine aggregate with steel slugs and placing them in the formworks. Most of the time serpentine sand is used to make the grout for filling the voids in compacted aggregates in the formwork. In order to avoid a lot of fine aggregate dust in the mixture, special care should be taken in locating the serpentine quarry. Coarse serpentine and sand must be relatively tough and free of fibrous materials which keeps the grout from penetration into preplaced coarse aggregate.

Serpentine rock is available in many different parts of the United States and Canada. Mostly it is used as ornamental stone or terrazo chips. Use of serpentine aggregates as shielding aggregate began in 1958 when it was considered as a possible shielding material by APD (Atomic Power Development Associates, Inc.) for the first time. Serpentine coming from a mine near Asbestos, Quebec was the first one to be experimented in construction studies of the Enrico Fermi reactor. The concrete made with this aggregate was 108 pcf and had a low compressive strength and high shrinkage. Since coarse aggregate had specific gravity of 2.60, all of these defective attributes were due to fibrous fine aggregate. However, in searching for a suitable material over 100 samples were obtained from 25 suppliers in western America. Information was gathered about all of these samples and tests were run as well.

In spite of vast distribution of serpentine in the nature, only limited number of deposits have suitable shielding material. Serpentine which is dense, sound, unfriable, and strong are low in bound water and those which are high in bound water are weak, slickensided, and friable more or less. On the other hand, some types of serpentine are not usable for both coarse and fine aggregate, since crushing process necessary in making sand will release the chrysotile fibers. Most of the western serpentine rock might contain a small fraction of chrysotile and vary quite considerably in water content and other physical properties. After testing different sorts of serpentine, several tons of serpentine were bought from the Sonora Marble Company in Sonora, California, from which coarse and fine aggregates were made for testing the PA casting method. Sand, in turn, was used in the grout mixture. There were some tests about the performance of the PA method for placing serpentine-iron concrete in limited areas. The concrete weighed 226 pcf and the sand grout was 128 pcf.

Properties of Serpentine Aggregates

Chemically it is magnesium silicate ($3Mgo.2\ SiO_2.2H_2O$) which is composed of 44.1% silica, 43.0% magnesia, and 12.9% water. It often consists of a massive structure but microscopically is fibrous. Its hardness varies between 3.5 and 5.0 and has a specific gravity of 2.5 to 2.65. It occurs in altered igneous rocks and in metamorphics as well and sometimes in such quantities to make up the entire rock mass. Table I provides some information about the samples which were obtained from different sources at the time of bidding for neutron production reaction shielding. All specifications for the NPR project are identical with ASTM C637-69T, "Aggregates for Radiation-Shielding Concrete." With reference to the ASTM specifications, the amount of bound water is called the fix-water content. A heating test in which the water and volatiles are driven off is used to figure out the amount of fix water content and volatiles. An anhydrous absorber is used to determine the amount of water. From Table I it is seen that for the bid samples the amount of ignition loss is within 1.4 to 23.6 percent range. Since the bound water is 12.9 percent of the total weight, the difference will be volatiles. Some of the samples have desired water content but high values of abrasion loss. All of the samples coming from the West were practically free of chrysotile. Looking

Sample number	Ignition Loss, % by wt.★	Train (water), % by wt.★	Volatile % by wt.★	specific gravity	Percent Absorption	L. A abrasion Loss, %
1	1.45			2.68		
2	11.83	11.73	0.10	2.60		
3	16.41	11.29	>4.46	2.49	2.60	
3′	13.04	12.79	0.25			
4	3.99			2.90	1.1	
4-a	6.08					
5	12.12	11.66	0.46	2.55		31
6	15.11	10.62	4.91	2.65	1.1	
7	14.46	11.26	3.62	2.65	1.2	20
7-c	15.89	10.82	5.49			
8	23.62	7.91	>15.71	2.72	1.1	
8-c	18.19	9.10	>9.09			
9	11.94	11.71	0.57	2.62	1.5	26
9-c	12.05	11.79	0.62			
10	12.70	11.60	1.78	2.59	1.8	22
Specified value	10% min.	10% min.	2% max.	2.55	2.0	30% max.

Table 1 - Physical Properties Of Serpentine Samples for NPR Project

★ Based upon weight at 300°c, and ignition temperature of 900°
courtesy of ACI Special publication SP-34 on Concretes f

at samples 1, 4, and 5, which came from different quarries near John Day, Oregon, shows how much difference in properties of serpentine could be expected even within a limited area. Both samples 6 and 7 came from Chewelah, Washington, and were high in volatiles which made their use uncertain.

Sonora samples obtained were well free of chrysotile, but some of the grout sand had to be washed before using in NPR shielding project.

Changes in State of Fixed Water
Due to Temperature Rise

Up to about 500°C and with a temperature rise of 50°C per hour there is only a minor change in fixed water content. Further heating will lead to rapid water losses. So 500°C could be assumed the dehydration limit. Continuing to heat the sample above 500°C will be accompanied by dehydration continuation up to the time when sample loses all of its fixed water. Water changes up to 500°C are a surface phenomenon and usually no mineral change occurs in this stage. There is evidence that water changes in serpentine aggregate is time dependent and is affected by vapor pressure. Magnetite, which is present in most serpentine samples in low percentages, is responsible for some weight gain in heated aggregates due to oxidation.

Physical Properties of Iron Serpentine Concrete

Iron-serpentine concrete was used in two different attenuation slabs in the NPR shielding program. The concrete was made in conventional way and preplaced aggregate, PA method. The conventionally made mortar weighed 272 lb/ft^3 and 268 pcf air-dried. In order to reduce segregation, chilled iron shot was used instead of large pieces of iron. This concrete was used in slabs which were called slab set No. 1 later on.

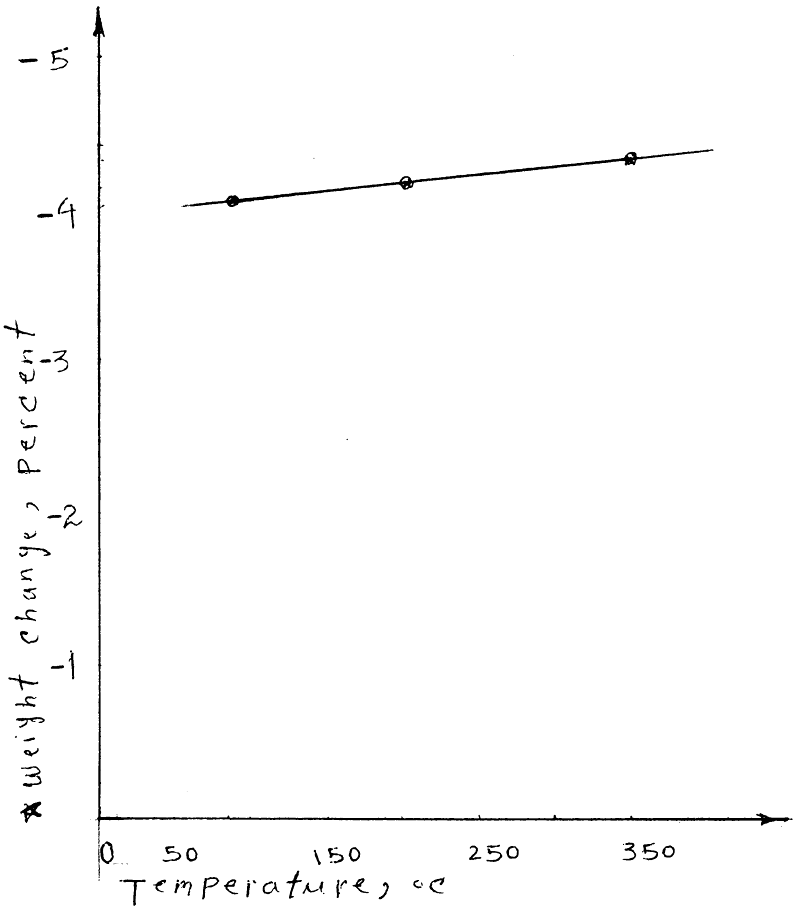


Fig. 2- Effect of heating temperature on weight changes of shielding Concrete (Iron-Serpentine) IS-265-M

Minus sign shows gaining weight due to iron oxidation

a for drawing the curve is furnished by ACI special publication,

gradation, % passing	Quebec Serpentine	Chewelah Serpentine	Sonora Serpentine
coarse			
1 - 1 ½ inch	97.7	100.0	100.0
1	67.8	70.6	77.4
3/4	39.6	49.2	43.1
1/2	15.0	17.1	12.6
3/8	6.1	6.6	3.0
NO. 4	3.0	1.8	1.3
Fine			
1/2 in.	100.0	100.0	100.0
3/8	100.0	94.0	90.0
NO. 4	80.8	68.1	49.1
8	55.2	37.9	28.1
16	36.0	19.8	15.4
30	23.4	10.3	9.1
50	14.0	6.0	5.4
100	8.00	3.4	3.6
specific gravity, SSD	2.59	2.66	2.61
Los Angeles abrasion, % wear at 500 revolution	21.7	19.8	26.2
unit weight, PCF Dry rodded	92.9	91.6	92.0
percent wt. Loss on heating, based on initial wt. at 20 oC			
85 oC	0.6	0.6	0.7
200 oC	0.8	0.7	1.2
350 oC	1.6	0.8	1.4
600 oC	11.0	8.6	2.4
900 oC	12.6	15.7	12.7

Table 2 - Results of different aggregate tests on three Serpentine Samples

courtesy of ACI special publication SP-34 on concretes

	Sonora Serpentine Grout Sand		
Sand gradation, percent passing	Job Sand	Washed Sand	Specs.
Sieve Size			
NO. 16	100	100	100.0
30	87	86	65-90
50	46	38	30-50
100	21	10	10-30
200	12	2	0-5
Fineness Modulus	1.46	1.76	1.30-1.90
Proportions by wt.			Ottawa Sand(C-109)
Sand/cement	1.33	1.33	1.33
water/cement	0.67	0.594	0.478
Fluidifier	1%	1%	1%
Flow, Seconds	17.9	18.2	18.0
Compressive Strength, psi			
7-day, 2-in. cubes	1570	1725	2510
28-day, 2-in. cubes	2225	2790	3510
Material having specific gravity less than 2.50	14%	7%	
Percent fibrous chrysotile, by weight			
NO. 16-30	1.0	0.4	
30-50	7.1	1.2	
50-100	2.6	1.7	
pan	4.2	1.4	
Total	14.9	4.7	

Table 3 - Effect of fibrus impurities on Properties of grout

Courtesy of ACI Special Publication SP-34 on Concretes

Sonora Serpentine Aggregates			
	Unwashed Sand	washed Sand	
job Location	Test Lab.	job sight	
Sand gradation, % passing			Specs.
NO. 16	100	100	100
30	88	82	65-95
50	51	32	30-50
100	25	8	10-30
200	11	1	0-5
Fineness Modulus	1.36	1.78	1.30-1.90
grout proportions by wt.:			
sand/cement	1.30	1.28	
water/cement	.64	0.52	
Fluidifier, %	1.2	1.2	
Flow, seconds	22	17	
unit wt., pcf.	124	128	

compression Tests	2x2 Grout cubes		6x12 concrete cylinders. ★	
Grout Sand	unwashed	washed	unwashed	washed
compressive strength, PSI				
7-days cured	2,300	2,880	1,560	2,250
28-days cured	3,400	4,636	2,075	3,790
unit weight, pcf	126	127	227	224

Table 4- Detrimental effects of Fibrus Material (Chrysotile) on the Properties of both grout and Preplaced Aggregate type of Concrete

★ Preplaced Aggregate consisting of 110 Lb. steel slugs and 55 Lb. coarse serpentine

Courtesy of ACI special Publication SP-34, Concrete For

In the case of PA concrete, the preplaced aggregate which was a combination of coarse serpentine and steel slugs weighed about 165 pcf when compacted in forms. Steel slugs weighed 110 lb and serpentine 55 lb. The voids of this combination was filled with portland cement grout made with fine serpentine aggregate with a unit weight of 128 pcf. When wet, this concrete weighed 226 pcf and it decreased to 221 pcf when air-dried. Tables V and VI contain useful information about the two kinds of concrete and portland cement grout. The unit weight of concrete made with Sonora serpentine coarse aggregate and sand conventionally is 143.00 pcf average and the difference to 265 pcf is due to the iron fragment.

The percent of length change of 0.154 percent at 350°C for IS-265-M should be considered as a source of stress producer inthe slabs, but in this case it is rather tolerable for the concrete.

There is a great reduction in dynamic modulus of elasticity due to temperature rise as shown in Table VI and Figure 3. The main change, however, is between 20°C and 85°C and consists of 60 percent reduction of the basic value of 5.8×10^6 psi. After 85°C the curve flattens more or less. Dynamic modulus of elasticity is measured by vibration of a prism or cylinder specimen to its fundamental transverse frequency, cycles per second, and by using Equation (1):

$$E = c\,W\,n^2 \qquad (1)$$

where

E = dynamic modulus of elasticity;

c = (for cylinder) $0.00416\ L^3T/d^4$, $\text{sec}^2/\text{sq in.}$;

W = weight of specimen, lb;

n = fundamental transverse frequency, cycles per second;

L = length of specimen;

Attenuation Slab set	NO. 1	NO. 2
Study item	Mortar	Grout
Mix	IS-265-M	S-128-G
Cement	Permanente	Permanente
Cement Type	II	II
Plastic Mortar Data		
Air content, Percent	2.7	2.7
Unit weight, PCF	265.2	128.0
Consistency		
Flow in Seconds		18
Flow in percent	32	
Batch wt., Lb		
Sand	35.0	50.0
Steel shot, SAE 330	62.0	
Steel shot, SAE 1320	125.0	
Cement	28.0	49.5
Water	15.0	24.0
Fluidifier	0.28	0.5
Watercement ratio	0.54	0.48
Cement Factor, SK/cy	8.02	15.18
Sand Grading, Percent Passing		
No. 4	98.7	
8	52.5	100.0
16	43.3	96.0
30	13.1	76.9
50	5.4	43.5
100	1.4	14.5
200	—	3.5
Fineness Modulus	3.86	1.69
Type of Serpentine Sand	Quebec	Sonora
G_s, SSD	2.59	2.62

Table 5 - Mix Data For Attenuation Slabs

Courtesy of ACI Special Publication SP-34, Concrete

Mix (From table 5)	IS-265-M	S-128-G	Specimen
Unit weight, pcf	279.0	137.2	2x2 x11 in. beams
Weight change, Percent			
28 days at 20 C	0.25	0.87	"
After heating at 85 °C	-4.03	-12.80	
200 °C	-4.12	-15.17	
350 °C	-4.31	-16.50	
Length change, %			"
28 days at 20 °C	0.007	0.010	
After heating at 85 °C	-0.036	-0.106	
200 °C	-0.037	-0.222	
350 °C	-0.154	-0.246	
Dyn. mod. elast., psi x 10⁶			"
28 day at 20 °C	5.8 (100%)	2.85 (100%)	
After heating at 85 °C	2.39 (41%)	2.33 (82%)	
200 °C	2.21 (38%)	1.83 (64%)	
350 °C	1.90 (33%)	1.32 (46%)	
Coef. of therm. expansion in/in./°C x 10⁻⁶			"
28 days at 20 °C	13.19	9.38	
After heating at 85 C	14.63	11.21	
200 °C	14.32	10.78	
350 °C	13.18	10.96	
Flextural strength, psi			"
28 days at 20 °C and after heating at 350 °C	840	526	
Modified cube compression after heating at 350 °C	6,900	5,770	
Thermal conductivity, BTU/ft-hr-°F			6x12 in. cylinder
Moist 20 °C	1.063	0.772	
Dry 85 °C	0.168	0.158	
200 °C	0.196	0.193	
350 °C	0.284	0.283	
Compressive strength, psi			2 in. cubes
28 days at 20 °C	9,680 (100%)	6,020 (100%)	
After heating at 85 °C	12,230 (113%)	7,460 (124%)	
200 °C	11,490 (126%)	6,420 (107%)	
350 °C	7,442 (82%)	5,170 (86%)	
Percent weight loss of 200 gr. samples			crushed mortar
20-900 °C	-28.8 ★	16.4	
85-900 °C	-28.3	14.9	
200-900 °C	-27.0	13.1	
350-900 °C	-29.2	12.0	

Table 6-The test results about Iron-Serpentine Concrete

★. Minus sign shows an increase in weight due to iron oxidation at extreme temperatures

Courtesy of ACI special publication SP-34, "Concretes for nuclear

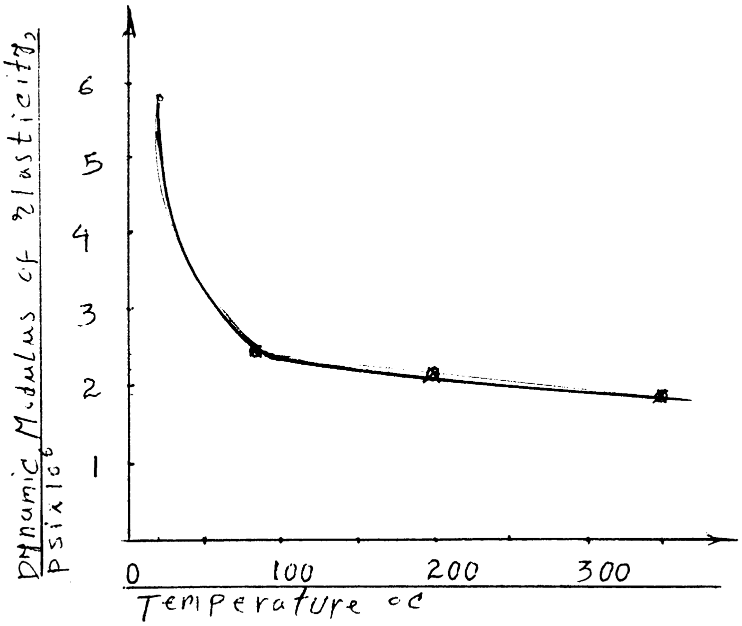


Fig. 3 - Effect of elevated temperatures on the dynamic Modulus of Elasticity of Iron-Serpentine Concrete IS-265-M used for Construction of Attenuation Slabs.

or drawing Fig. 3 is furnished by ACI special publication, Vol. III

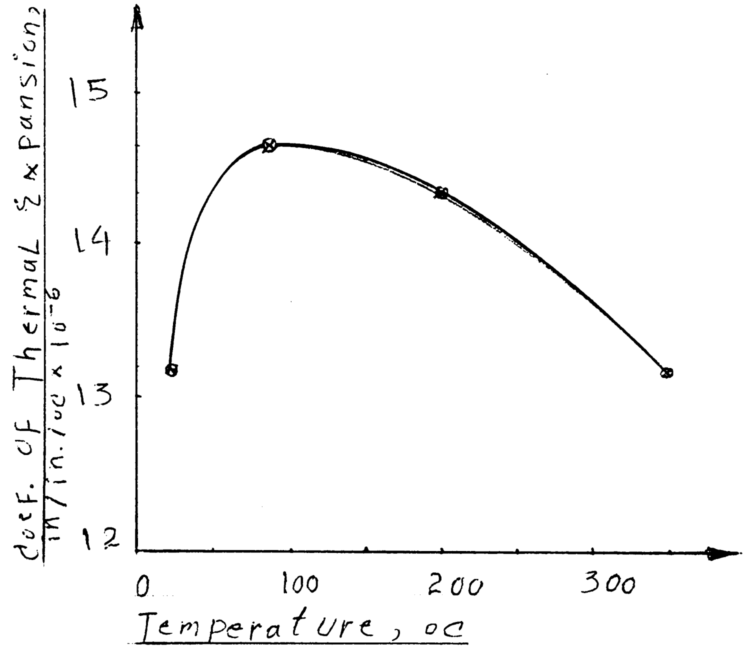


Fig. 4 - variation of thermal coef. Of expansion with temperature for the IS-265-M mortar used for attenuation slabs

a for drawing Fig. 4 is taken by ACI special publication, D = diameter of specimen; and

T = correction factor proportional to K/L, $\frac{\text{Radius of Gyration}}{\text{Length of Specimen}}$.

Since the dynamic modulus is the amount of initial tangent modulus of elasticity which is correct for low stresses only, its interpretation value is less than secant or other tangent modulus.

There is a gain in compressive strength of specimen when heated to 85°C and 200°C which turns to a loss when continue heating to 350°C. The relationship is shown in Figure 5 and as it is obvious this does not correspond to the pattern of change for modulus of elasticity. Indeed, there has been quite a bit of discussion about the validity of dynamic modulus of elasticity. Different references insist on special dimension samples; mostly a ratio of L/D of 4 for the sample tests is recommended. In the case of the NPR project, this ratio is 2 surprisingly and might have been a source of misinterpretation. This method is rapid and should we want to measure the modulus of elasticity without damaging the sample or use it several times for investigation of different phenomena like temperature, freeze and thaw test, and others, it proves excellent but there are shortcomings as well. Quoting from Troxell, Davis and Kelly's text on composition and properties of concrete makes this fact more obvious: "This method is not sensitive to small changes inthe paste content of concrete and is materially affected by the heterogeneity of the mix, so that determination of the true modulus can not be assured."

In those studies such as flow of heat in concrete masses or temperature-volume studies which are rather important in radiation shielding problems due to the inherent temperature-making ability of such structures, the thermal conductivity, K, is a very important factor. However, there is a rather uncommon fact regarding the thermal conductivity of iron-serpentine concrete. Figures in Table VI show that K changes drastically when temperature rises

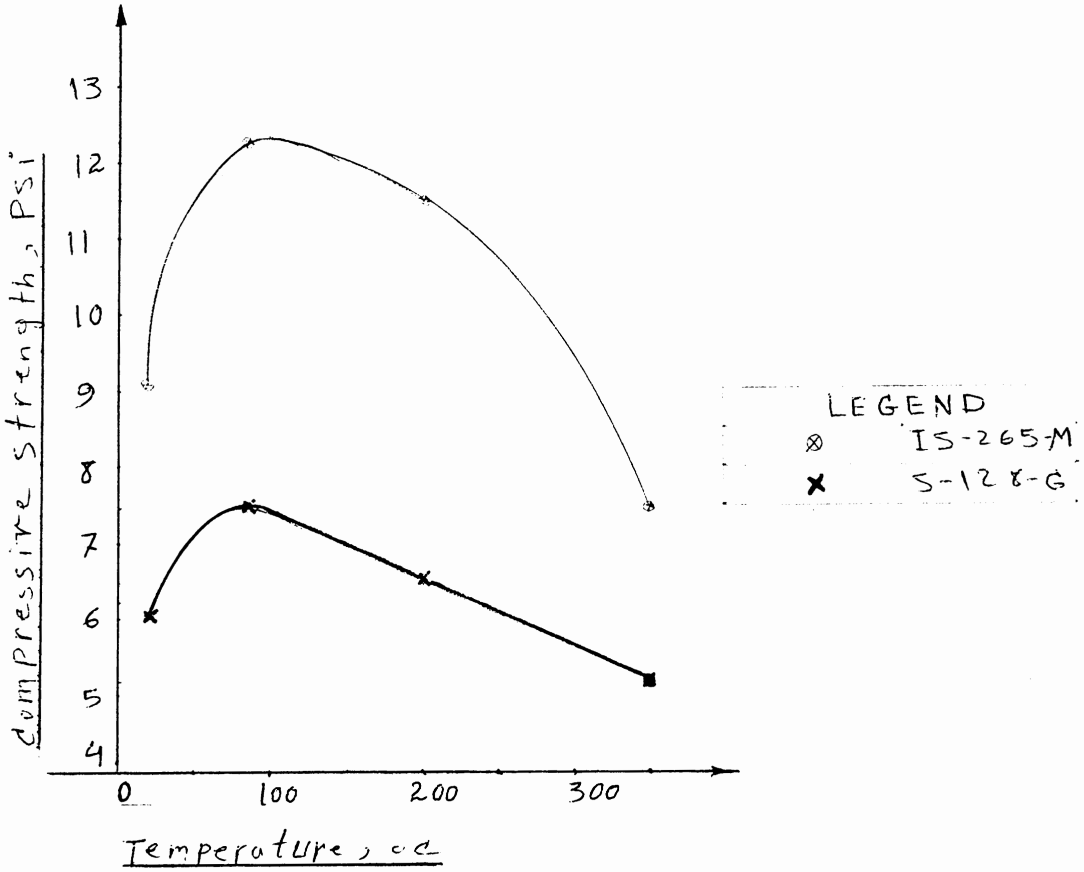


Fig. 5 - Relationship between Compressive strength and Temperature For IS-265-M and S-128-G Samples made with Serpentine Aggregate

is taken from ACI special publication SP-34, Vol. III from 20°C to 85°C. This is rather different from properties of ordinary concrete made with portland cement. Looking at the properties of ordinary concrete used in construction of the Hoover Dam in Troxell, Davis and Kelly text, there is only a very slight reduction in K when temperature rises from 10°C to about 65°C, something like (1.699 - 1.648). Also, the K value is very much higher in the case of ordinary portland cement concrete. For structures like power plants temperature relief is really important and low thermal conductivity which in turn causes low diffusivity is likely to lead to high concrete temperatures and high stresses due to the temperature. Thermal diffusivity could be calculated from Equation (2):

$$D = \frac{k}{Sd} \qquad (2)$$

where

D = thermal diffusivity, sq ft/hr;

S = specific heat of concrete, Btu/lb/°F; and

d = density, pcf.[1]

Shielding Properties of Iron-Serpentine Concrete

The ultimate task of every concrete used as shielding material, absorption of radioactive radiation, or shielding another word, is usually determined by inserting the test slabs in the vertical test wells of a formerly made source of radiation. In the case of iron-serpentine heavy weight concrete, the two different slabs made using different placement methods were tested by placing them into test wells located in the top shield of the 105-DR Hanford reactor. A series of neutron detectors were installed between each

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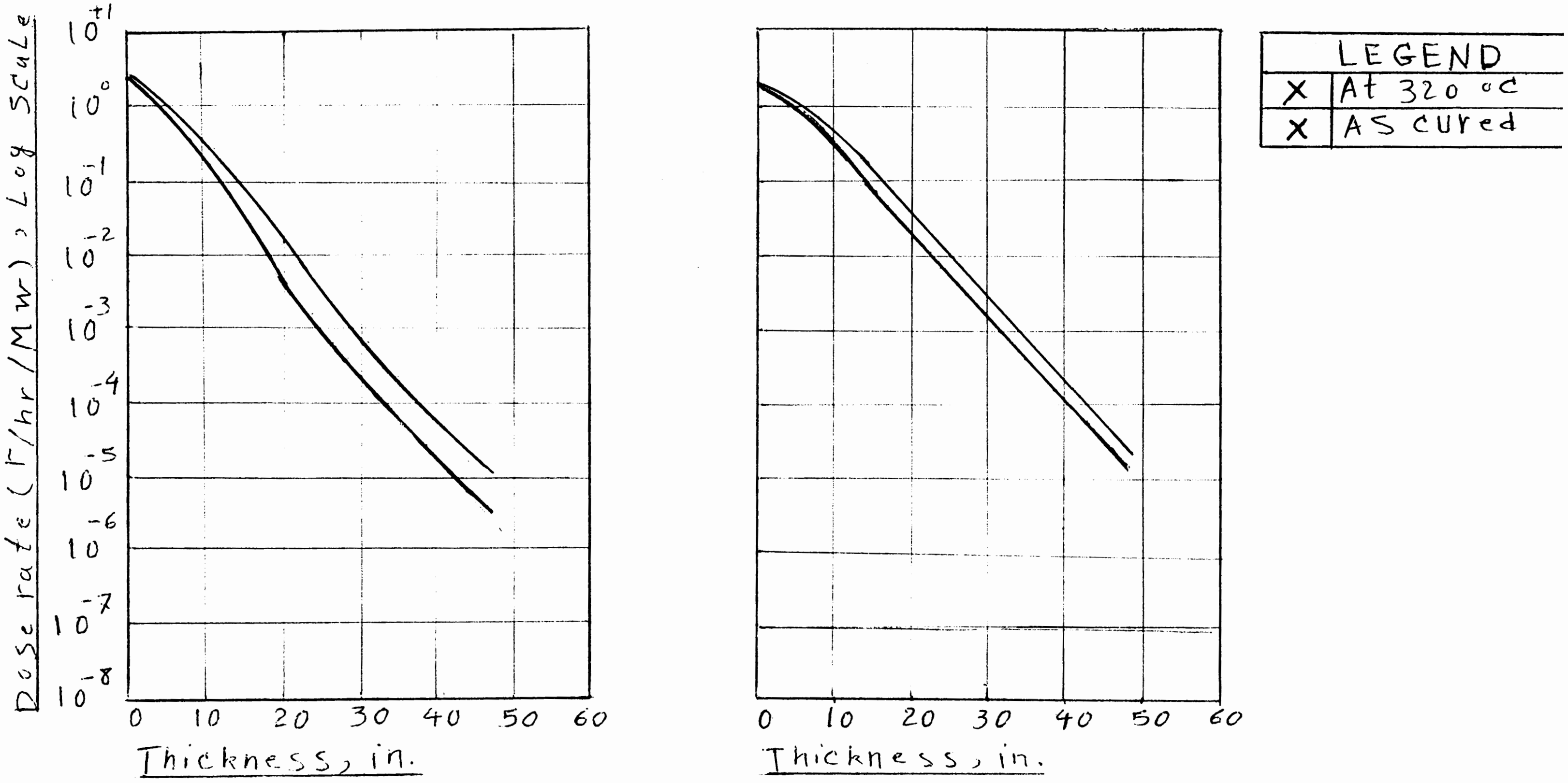
[1] Courtesy of Troxell, Davis, and Kelly textbook on Composition and Properties of Concrete.



Attenuation set No. 1
(IS-268-C concrete)

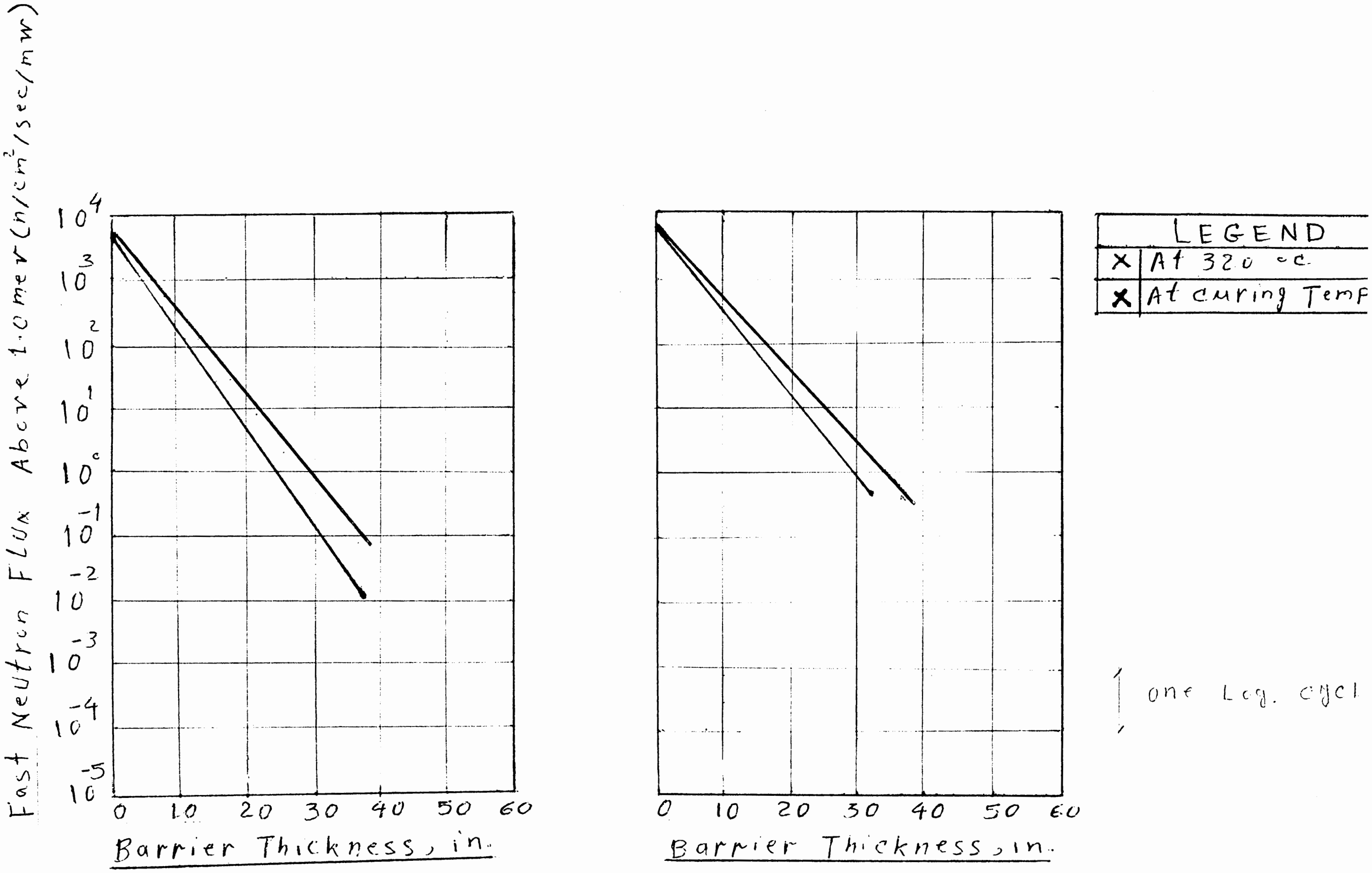
Attenuation set No. 2
(IS-220P concrete)

Fig. 6 - Relationship between the Slab Thickness and Gamma ray intensity in Iron-Serpentine Concrete

slab to determine both lateral and transverse distribution of penetrating neutrons. The concrete slabs were cured for 28 days and at the end of this period were air-dried. The initial weight of the slabs was measured and then they were inserted in the wells. Upon the completion of shielding measurements, slabs were taken to the oven and heated to a constant weight at 100°C. Then they were let to cool down to room temperature after which they were weighed again and inserted into the test well again. Neutron and gamma radiation measurements were then taken place on the oven-dried slabs and the process was repeated with 320°C temperature. Every neutron and gamma measurement was done at test well temperature of 30°C approximately. Weight measurements taken before and after placing slabs in the test wells show that no moisture change occurred while in test wells.

As far as the neutron attenuation is concerned, the data obtained in these NPR test concretes correspond with the former experience scientific results that the higher the water content of concrete the better the shielding properties of attenuation slabs. Figure 7 shows this fact comparing IS-268-C concrete of higher water content to IS-220-P concrete with a lower W_c. As it is indicated in Figure 7, all other conditions equal IS-268-C concrete is about 5 to 55 times more effective in shielding properties than IS-220-P. Also, the high temperatures are likely to reduce the potential of both concretes for radiation reduction and this is more serious in the case of higher water content, IS-268-C.

Also presented are the values of removal cross section for fast neutron in Table VII. The term cross section, in spite of being identified by sq cm, is really a measure of probability of occurrence of the process for which it is given. For example, in the case of fast neutron flux, a large cross section indicates a very high probability of occurrence of such a flux, while



Attenuation set No. 1
(IS-26 r-c concrete)

Attenuation set No. 2
(IS-220 P concrete)

Fig. 7 - Fast Neutron distribution in two different Iron - Serpentine concretes with different Unit weights

Concrete designation	IS-265-c			IS-220-P	
curing condition	Initial Air-Dried	100 °c	320 °c	Initial Air-Dried	320 °c
Density					
gr/cm3	4.298	4.187	4.161	3.538	3.384
pcf	268.2	261.3	259.3	220.8	211.20
Removal cross-section, cm^{-1}					
measured ΣR	0.127	0.113	0.110	0.110	0.099
computed ΣR	0.122	0.111	0.109	0.122	0.106

Table 7 - Density and Cross section Characteristics of Concretes used as Attenuation Slabs under different curing Conditions

a small cross section indicates that few such occurrences will be found. If the cross section is multiplied by the number of atoms per cu cm, the result will be the absorption coefficient μ for the process, with a unit of cm^{-1}. As shown in Table VII, the absorption coefficient for the process of neutron flux is larger in initial air-dried condition than it is at 100 and 320°C.

In the case of gamma ray shielding, as it was stated in the first part of this paper, density plays the major role in attenuation process. Comparing the results of gamma dose rate in two different attenuation slabs in Figure 6 proves the above state fact. The denser the concrete the more the attenuation efficiency of such a concrete for gamma ray shielding. The effect of temperature rise is identical with the neutron flux case.

Considering all the discussed results, figures, and tables, it is legitimate to state that the special types of shielding concrete developed and tested during the NPR shield program have excellent physical properties and high strength at room and elevated temperatures and adequate other properties like thermal conductivity, diffusivity, and shielding properties at elevated temperatures. Also, the results yielded prove that serpentine aggregates and hydrated portland cement provide enough hydrogen, water, and other light elements necessary for effective attenuation of neutrons when used with high-density aggregates such as steel slugs or iron shot and at elevated temperatures.

The data obtained during these sets of tests were used successfully for design and construction of the inlet and outlet shields of the NPR project. These shields are subjected to maximum working temperature of 320°C as might have been observed and their functioning have proved satisfactory in the past service years.

HEAVY STEEL-AGGREGATE CONCRETE

Heavy steel-aggregate concrete is one type of a vast variety of concretes known as heavy weight concretes and which are used when there is a space limitation. In this part of the paper an experimental study of steel-aggregate concrete is done and a proportioning procedure for achieving concrete of given strength and density will be explained.

There was great attention toward heavy weight concretes from the very frist step toward construction of nuclear power plants. It was long known that the effectiveness of a barrier in decreasing neutron flow is a factor of $(e)^d$ where e is the base of natural logarithm and d is the density of the barrier's material. So doubling the density of the material will increase the effectiveness against radiation by $(2.718)^d$ times. So efforts were started to make concretes with feasible economy and densities higher than 300 pcf preferably. In order to achieve this goal using steel punching and steel shots are quite adequate. Both of these steel types are considered inert ingredients of concrete since they do not participate in the chemical reactions leading to hardened concrete. Other ingredients used are identical with ordinary portland cement concrete which are water, cement, admixture, and of course some air. Untreated water proves satisfactory to use as long as it is free of clay minerals and/or organic impurities. Portland cement type I is the only type which was used in the series of experiments for developing the proportioning method. One pound of admixture per bag of cement was added. This was a two-purpose admixture to entrain air and disperse cement which in turn contributes to greater strength and workability. The steel punchings were inexpensive material, mostly the waste of steel fabricating shops. The pieces were constituted mainly of flat and circular geometries and their maximum diameter was 1 inch, and 3/8 of an inch was about the maximum thickness.

However, there could be found some abnormally long and flat pieces among others. While it is proven that rust has not any effect on cement hydration, it should be said that it delayed the time of set for the concrete by three hours. However, even with this additional three hours, the setting time was still well below ten hours setting time which is the ASTM standard.

The need for fine fragment was fullfield using steel shots which were spherical and their gradation consisted of particles retaining on No. 4 to particles passing a No. 100 sieve. This fine aggregate was artifically combined to get a fineness modulus of about 4.0. The specific gravities and dry densities are presented in Table I.

Optimum Mixture of Ingredients

After physical properties of concrete ingredients, proportioning is the most important factor in quality control. The term "shot factor" is used to introduce the relative porportions of the inert materials. It is defined as the ratio of fine aggregate to total aggregate. In the case of ordinary concretes either optimum workability or otpimum density is used to determine shot ratio. However, in heavy concrete optimum density is more used since workability is not greatly significant due to placing methods. The dry packed densities of steel punchings and steel shot are given in Table I. The mixture of the two will almost produce greater densities. The greatest density which is the most desirable could be measured by trial and error combinations of limited weight (not to exceed 5 lb) with a selected shot factor. By mixing alternate layers of shot and punching in a container and taming to the greatest possible compaction, the dry packed density could be measured for different shot factors. The results might be plotted as shown in Figure 1.

Ingredient	sp. Gravity	Dry packed density, pcf.
water	1.00	
cement	3.10	
steel punching	7.56	248.00
steel shot	7.46	297.00

Table 1 - sp. gravities and density of concrete ingredients

Courtesy of ACI Journal proceedings V.52, Sept. 1955

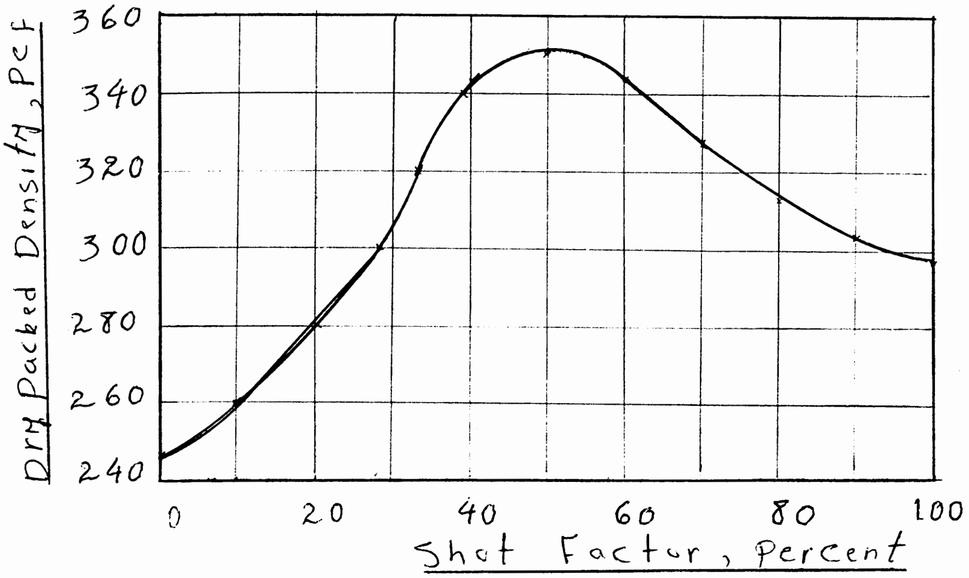


Fig. 1 - Variation of dry packed density with different shot factors

Courtesy of ACI Journal Proceedings v.52 Sept. 1955

In the set of tests which are going to be discussed now, the maximum density of 352 pcf was reached with a shot factor of 50 percent.

The theoretical maximum concrete density is then calculated by assuming the voids filled with concrete paste completely (zero air voids). It is apparent that cement paste should be at its maximum possible density to obtain maximum concrete density. The rule is that the lowest the water cement ratio the highest the paste density but water-cement ratios lower than 3.5 gal per bag of cement are not practical due to the restrictions like plasticity and excessive shrinkage of dry mixes and others as well. Considering all of these facts the maximum theoretical density is 384.1 pcf for heavy concrete (Table II).

Since the 50 percent shot factor proved to produce the maximum density, it was held constant. However, different test batches were produced using different water cement ratios and cement factors. Two standard 6 x 12 in. cylinders and one 6 x 6 x 30 in. beam were made by each test batch. The sufficiently mixed concrete was placed informs and compacted by means of vibrators. After two days the samples were removed and sprayed with a kind of protective membrane. A cement factor of 7.00 bags/cu yd and a water cement ratio of 3.5 gal/bag of cement produced the densest concrete of acceptable plasticity and workability. Any smaller cement factor would leave unfilled voids in the concrete mass.

The selection of water cement ratio and cement factor should be corresponding to the density and strength desired in those occasions when strength controls the design criteria. The strength depends on desnity of concrete completely and for any one strength there is not but one density.

For any design practice there should be an investigation to see whether the minimum density criteria or the minimum strength controls. The density

Ingredient	sp. gravity	Specific Weight, pcf	Weight per cu ft of Concrete, Lb	vol. cu ft
water	1.00	62.4	7.62	0.1221
cement	3.10	193.4	24.51	0.1267
Punching	7.56	471.7	176.00	0.3731
shot	7.46	465.5	176.00	0.3781
concrete			384.12	1.000

Table 2 - Proportions for getting Theoretical Max. Concrete Density

Courtesy of ACI Journal v. 52, Sept. 1955

may then be selected accordingly. Knowing the desired density, a proportion could be found to produce it. There is a choice between keeping the water cement ratio fixed and changing the cement factor or fixing the cement factor and determining the most desirable water cement ratio. In no case should the cement factor get less than 6 bags per cu yd. Using higher water cement ratios justifies lower cement factors but then it is necessary to use more shot and punchings and there might be a drop in the strength too. In large projects a precise economy study for the best selection of water cement ratio and cement factor is justified.

Figures 3 and 4 show that there is a constant increase in both flexural strength and modulus of elasticity with increasing theoretical density. Figure 5 shows the relationship of cement factor, water-cement ratio, and theoretical density for the type of concrete under investigation.

Sample Design Problem

The objective is a heavy concrete with a minimum density of 350 pcf and a 7-day compressive strength of 4500 psi. Looking at Figure 2 it is seen that for a 7-day strength of 4500 psi a minimum theoretical density of 365 pcf is required. From Figure 5 it is apparent that there are too many combinations of water-cement ratio and cement factor that will give a density of 365 pcf. No cement factor less than 7 bags per cu yd is permissible, so this is the minimum CF mentioned in Figure 5. Considering CF = 7, it is seen that a water-cement ratio of 4.9 gal per bag would produce the desired density of 365 pcf. However, if the minimum water cement ratio of 3.5 gal/bag is used, the cement factor increases to 8.65 bags per cu yd accordingly. A CF of 8 bags per cu yd with a water-cement ratio of 4 gal per bag is satisfactory too. These three combinations are selected and the following show the proportioning

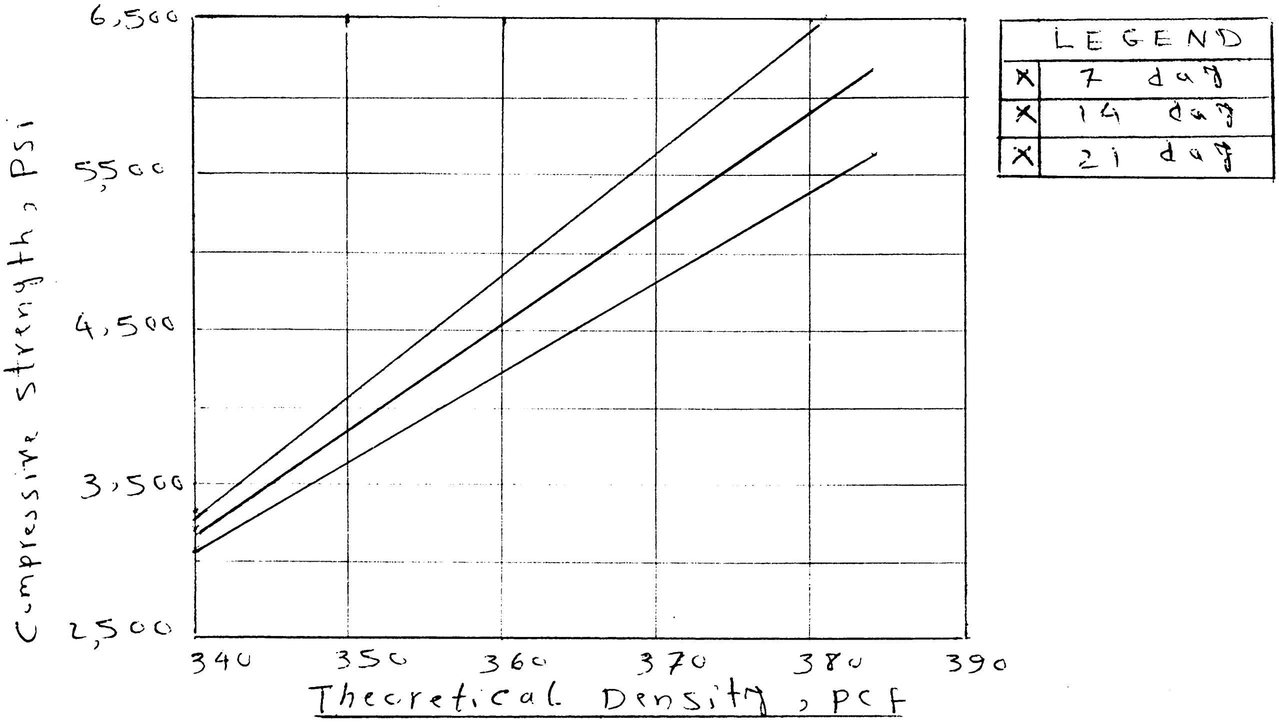


Fig. 2 - Relationship between theoretical density and 7, 14, and 21 days compressive strength

Courtesy of ACI Journal V.52, Sept. 1955

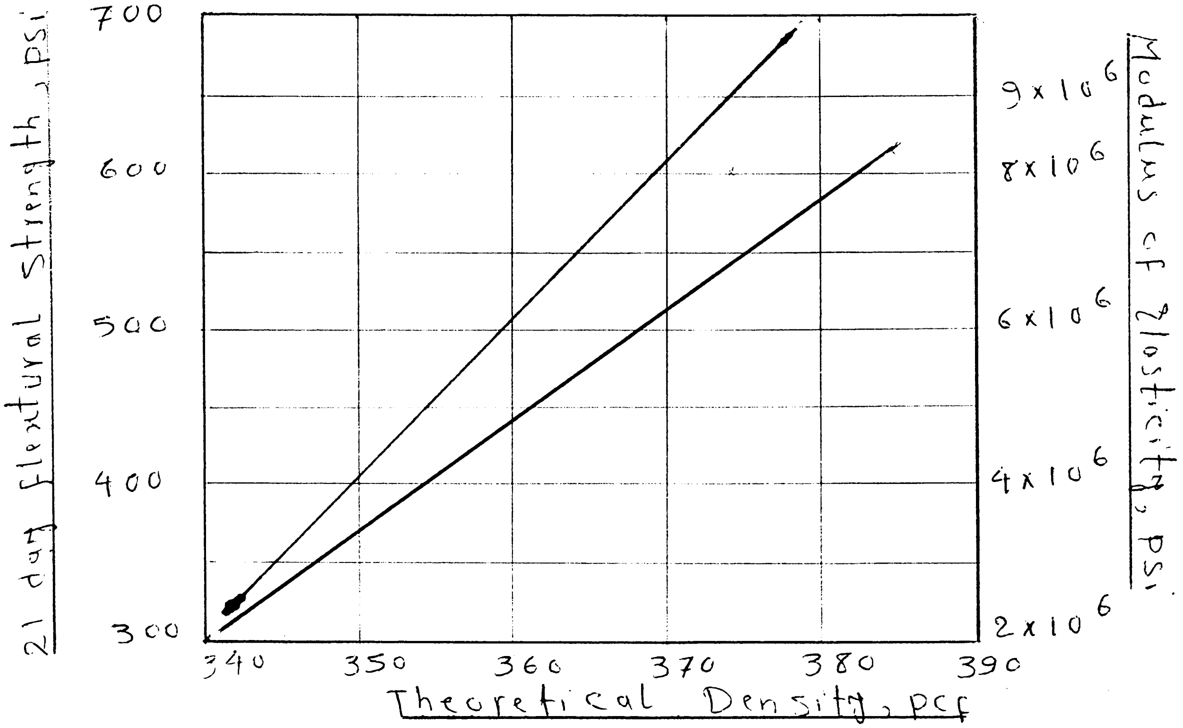


Fig. 3 and 4 - Relationship among theoretical density, flextural strength and elasticity

LEGEND	
x	mod. of elasticity
x	flex. strength

Courtesy of ACI Journal v. 52, Sept. 1955

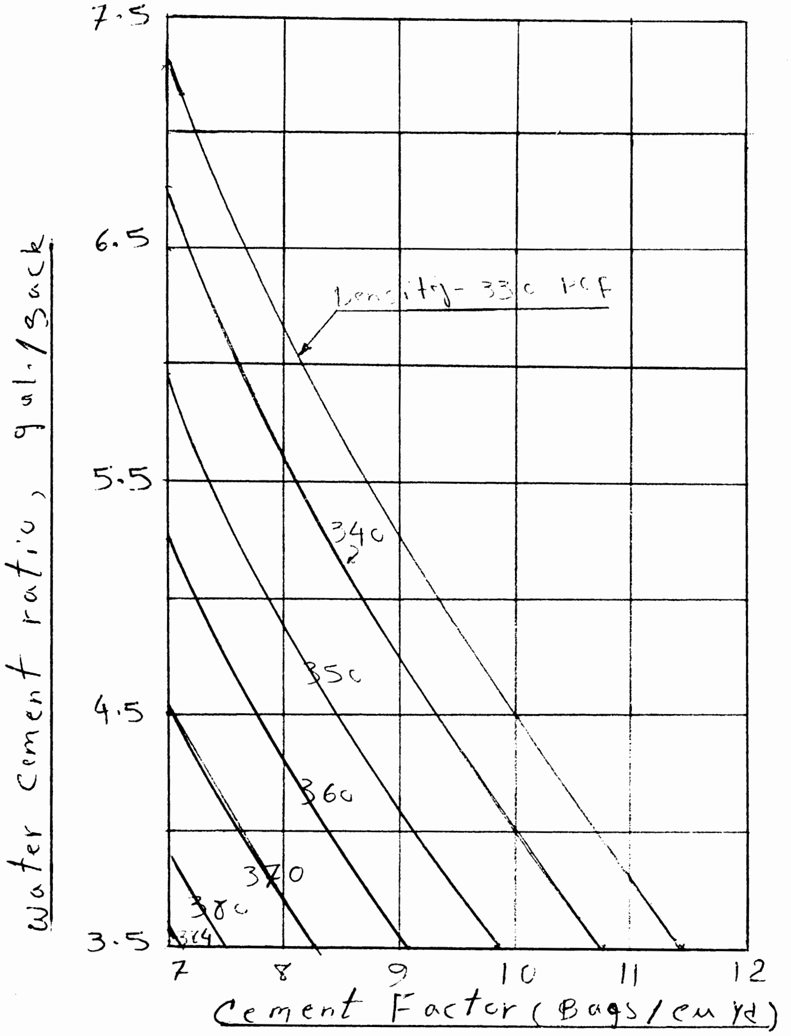


Fig. 5. Relationship of water cement ratio, CF, and density

Courtesy of ACI journal v. 52, Sept. 55

calculations for ingredients of these combinations. A summary of calculated values is given in Table IV.

1. CF = 7 bags/cu yd, W/C = 4.9 gal/sack

$$\text{Weight of cement per cu ft of yield} = \frac{7 \text{ bag/cu yd} \times 94 \text{ lb/bag}}{27 \text{ cu ft/cu yd}}$$

$$= 24.4 \text{ lb/cu ft}$$

$$\text{Weight of water per cu ft} = \frac{4.9 \text{ gal/sack} \times 24.4 \text{ lb/cu ft}}{94 \text{ lb/sack} \times 0.1198 \text{ gal/lb}}$$

$$= 10.6 \text{ lb/cu ft}$$

2. For CF = 8 bags/cu yd; W/C = 4 gal/sack

$$\text{Weight of cement per cu ft} = \frac{8 \times 94}{27} = 27.9 \text{ lb/cu ft}$$

$$\text{Weight of water per cu ft} = \frac{4 \times 27.9}{0.1198 \times 94} = 9.9 \text{ lb/cu ft}$$

3. For CF = 8.65 bags/cu yd; W/C = 3.5 gal/bag

$$\text{Weight of cement per cu ft of concrete} = \frac{8.65 \times 94}{27} = 30.1 \text{ lb}$$

$$\text{Weight of cement per cu ft of yield} = \frac{8.65 \times 94}{27} = 30.1 \text{ lb/cu ft of yield}$$

$$\text{Weight of water per cu ft of yield} = \frac{3.5 \times 30.1}{0.1198 \times 94} = 9.4 \text{ lb.}$$

Batch No.	W/C gal./bag	C.F bags/cu yd	Theoretical density PCF	Actual density PCF	Compressive σ, psi			Flextural Strength psi	E x 10^{-6} psi
					7 day	14 day	21 day		
P 1	4.5	6.3	381	376	2860				
P 2	4.5	7.0	372	376	4310				
P 3	4.5	8.3	353	353	4330				
P 4	4.5	9.0	342	352	3730				
P 5	3.5	7.0	384	371	5390	5460	3220*	615	6.14*
P 6	4.00	7.0	377	377	5270	4490	6080	462	8.33
P 7	4.25	7.0	370	375	4440	4030	5430	425	6.77
P 8	3.5	8.0	372	372	4880	6400	6380	384	6.95
P 9	4.00	8.0	364	370	4690	5760	5290	354	7.50
P 10	4.50	8.0	357	361	3960	4600	4260	462	3.85
P 11	3.50	9.0	361	356	4930	4850	5320	567	7.42
P 12	4.00	9.0	352	353	3980	4190	4190	405	4.22
P 13	4.50	9.0	342	343	2760	3130	3220	329	2.92

* - poor specimen

Table 3 - Test results on cylindrical and beam specimens

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Ingredient	w/c = 4.9 gal/bag CF = 7 bags/cu yd		w/c = 4.0 gal/bag CF = 8 bags/yd^3		w/c = 3.5 gal/bag CF = 8.65 bags/yd^3	
	wt. Lb per cu ft of yield	volume cu ft	wt. Lb per cu ft of yield	volume cu ft.	wt. Lb per cu ft of yield	volume cu ft
shot	164.8	0.3541	163.4	0.3511	162.70	0.3495
punching	164.8	0.3494	163.4	0.3464	162.70	0.3448
cement	24.4	0.1260	27.9	0.1440	30.70	0.1557
water	10.6	0.1705	9.9	0.1585	9.40	0.1500
concrete	364.6	1.000	364.6	1.000	364.90	1.000

Table 4 - Quantities of ingredients for three different combinations.

Courtesy of ACI Journal, v.52, Sept. 1955

CONCLUSIONS

An economical study might be done knowing the prices of steel shot and punching and cement after which the most efficient mix could be selected.

Test results show an increase in strength with the length of curing period, with reduction of water content and with density of concrete. Inasmuch as the strength of ordinary concrete increases with increasing cement factor, the very opposite is true about heavy concrete. This emphasizes the fact that the strength of heavy weight concrete increases with its density, because the decrease in water-cement ratio and the decrease of CF both increase the density of heavy concrete. This is true because the density of aggregate in ordinary concrete is less than cement while the opposite is true in the case of heavy concrete.

The largest variation of theoretical as compared to actual densities is less than 3 percent. The theoretical density can be determined before a test batch is made. Observations of all fractured specimens indicated a well-mixed and integrated concrete with good workability and an overall appearance similar to ordinary concrete but superior in radiation reduction.

Two kinds of heavy weight concretes which were discussed are not the only options available to engineers. There are other types of heavy concrete with their own efficiencies and/or deficiencies. There are also other uses for these types of concrete which of course were not related to the subject of this paper. Although the main purpose of this paper is to gather some useful information about radiation shielding, the complication of the subject is so that the paper should not be regarded but the very first step for understanding the rules concerning radiation shielding patterns. However, with the scale of undesired problems which occur in the industry and with growing degrees of concern of people about the sanitary nature of their environment, the field of study seems vastly open to interested parties and with this regard practical surveys are of the greatest value.

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