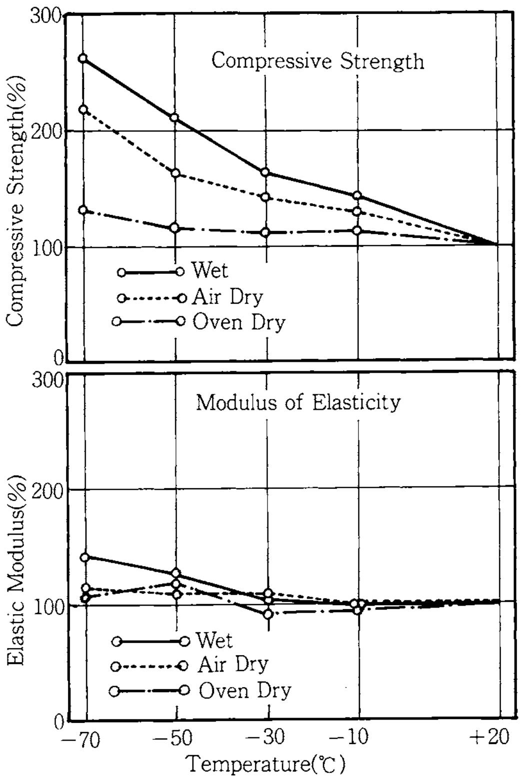

Fig.I PROPERTIES OF CONCRETE AT LOW TEM-
PERATURES EXPRESSED AS PERCENTAGE TO
NORMAL CONCRETE

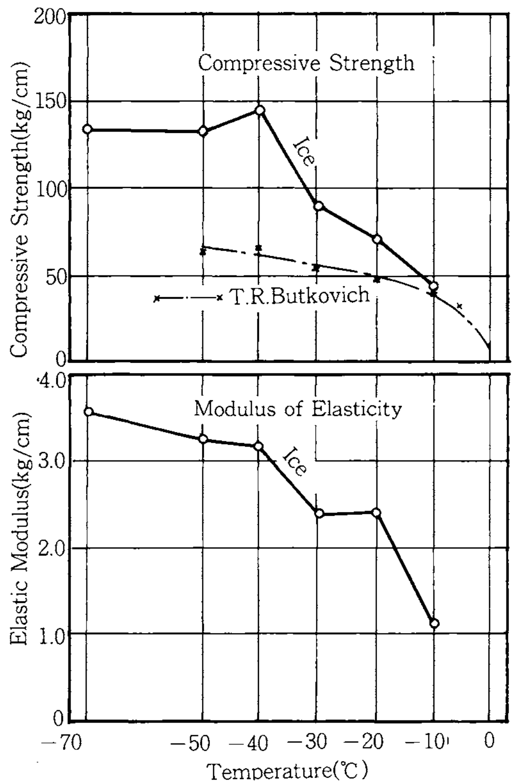

Fig.2 PROPERTIES OF ICE AT LOW
TEMPERATURES

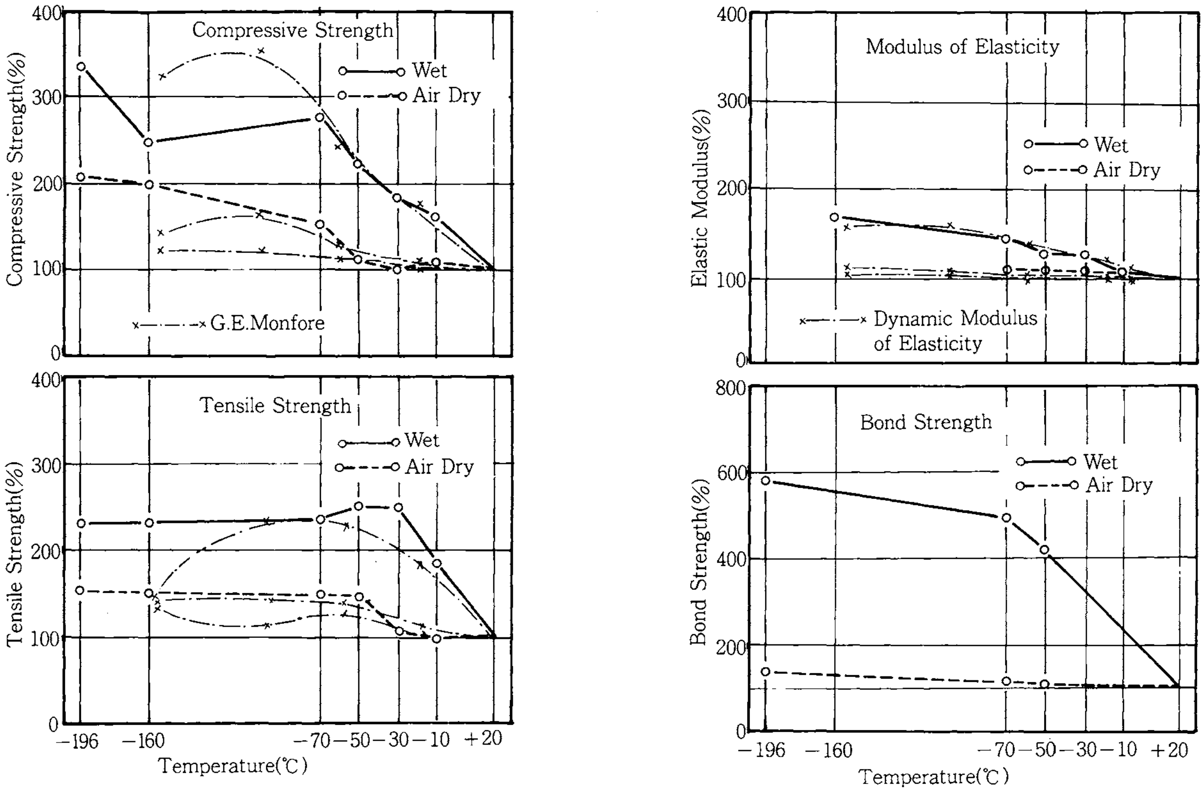

Fig.3 PROPERTIES OF CONCRETE AT VERY LOW TEMPERATURES
EXPRESSED AS PERCENTAGE TO NORMAL CONCRETE

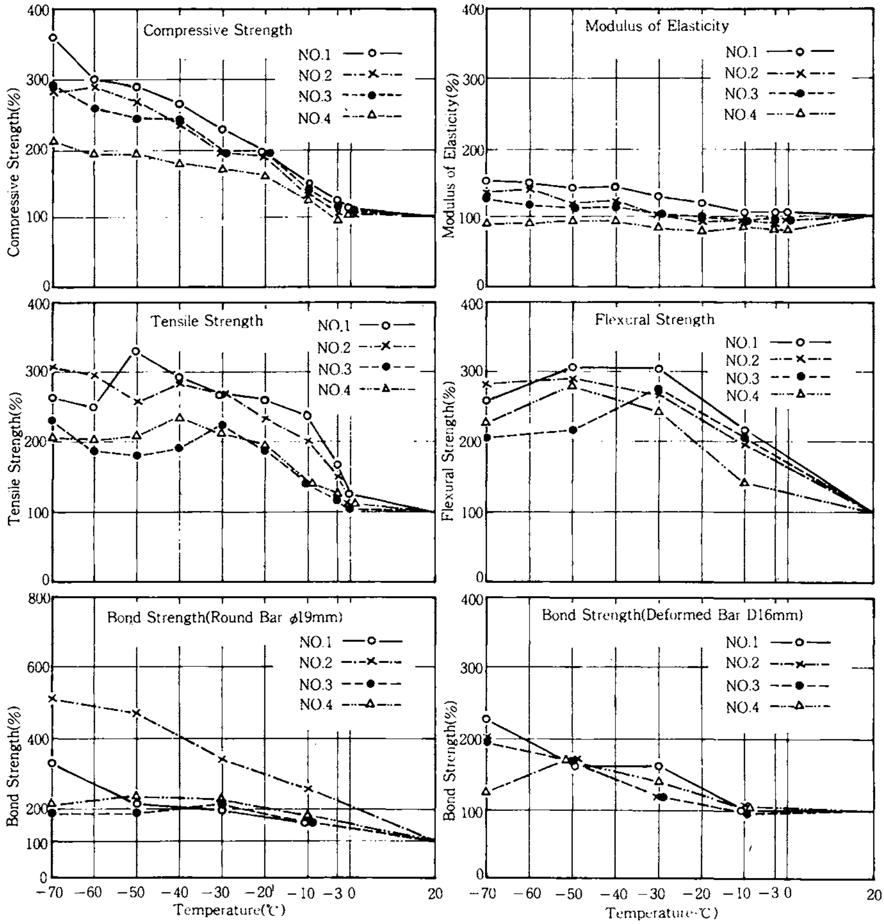

Fig.4 PROPERTIES OF CONCRETE AT LOW TEMPERATURES EXPRESSED AS PERCENTAGE TO NOMAL CONCRETE AT 20°C

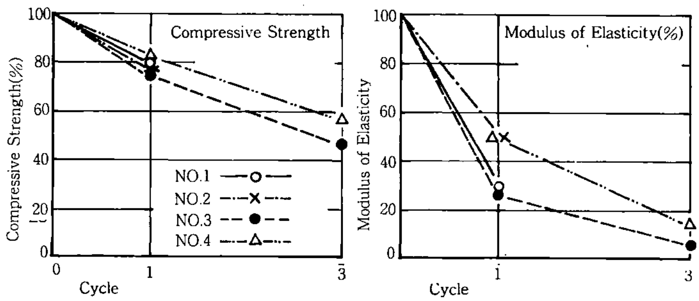

Fig.5 STRENGTH OF CONCRETE SUBJECTED TO FREEZING AND THAWING CYCLES IN THE RANGE OF 20°C AND -196°C

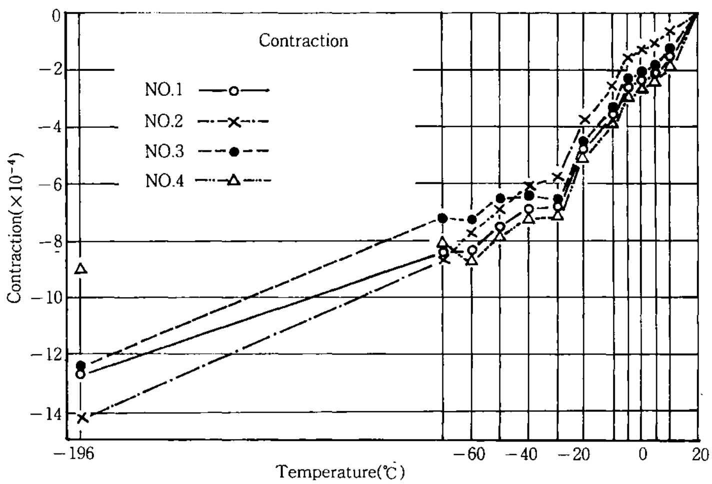

Fig.6 CONTRACTION OF CONCRETE AT LOW TEMPERATURE

SP 55-10

The Effects of Nuclear Radiation on the Mechanical Properties of Concrete

By H.K. Hilsdorf, J. Kropp, and H.J. Koch

Synopsis: Previously published experimental data on the effect of nuclear radiation on the properties of plain concrete are summarized and evaluated. Neutron radiation with a fluence of more than 1×10^{19} n/cm^2 may have a detrimental effect on concrete strength and modulus of elasticity. Thermal coefficient of expansion, thermal conductivity and shielding properties of concrete are little affected by radiation. Radiation damage is mainly caused by lattice defects in the aggregates which cause a volume increase of aggregates and concrete. Different aggregates show different radiation resistance so that the selection of suitable aggregates is the most important parameter in the design of a radiation resistant concrete.

Keywords: aggregates; compressive strength; concretes; creep properties; gamma rays; mix proportioning; modulus of elasticity; neutrons; radiation shielding; radiation tests; reviews; tensile strength; thermal conductivity; thermal expansion

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1. PROBLEM STATEMENT

Concrete is frequently used as a biological shield against nuclear radiation. For some structures such as prestressed concrete pressure vessels not only the good shielding properties but also the load carrying capacity of concrete are utilized. Under such circumstances also changes of the mechanical properties of the concrete due to nuclear radiation are of particular significance and may have to be taken into account in the design of such structures.

It is known that nuclear radiation influences some materials properties. Therefore, also concrete or concrete components may be influenced by nuclear radiation. To clarify this, experimental investigations have been initiated as early as 1944 in order to determine the influence of nuclear radiation on the mechanical properties of concrete (9). Such investigations have been intensified since concrete is considered as a structural material for reactor pressure vessels. In the following the experimental data resulting from such investigations are summarized and evaluated in order to answer the following principle questions:

(a) Does nuclear radiation influence the mechanical properties of concrete? Properties of particular significance are:
- compressive and tensile strength
- modulus of elasticity
- coefficient of thermal expansion and thermal conductivity
- shielding properties

(b) How high is the critical radiation dose above which significant changes in concrete properties are to be expected?

(c) Is this critical radiation dose below or above the dose to be expected in special concrete structures?

2. RELEVANT TYPES OF NUCLEAR RADIATION

Atoms are considered radioactive if they are transformed into other nuclides such as in the case of the decay of a nucleus while emitting radiation energy. The new nucleus formed in the decay process has an energy state which is lower than the energy state of the initial nucleus. The energy difference between both nuclei corresponds to the energy of the radiation emitted during the decay process. Various types of radiation may occur during such a process, however, only two are of relevance in the context of this paper:

2.1 Neutron Radiation

Neutron radiation occurs if electrically neutral particles are emitted e.g. during the radioactive decay of heavy elements with a surplus of neutrons in relation to the number of protons. We may distinguish between different types of neutron radiation depending on their energy: Thermal or slow neutrons, epithermal neutrons and fast neutrons. The following limiting values may be given:

thermal neutrons: energy $E < 1$ eV
epithermal neutrons: 1 eV $< E <$ o.1 MeV
fast neutrons: $E >$ o.1 MeV

In the following no distinction will be made between thermal and epithermal neutrons so that all neutrons with an energy $E <$ o,1 MeV will be considered thermal or slow, whereas neutrons with an energy $E >$ o,1 MeV will be considered fast.

To describe the intensity of neutron radiation two units are commonly used. The f l u x corresponds to the number of neutrons which penetrate a sphere with a cross-section of 1 cm^2 during a time period of 1 sec. The dimension of flux is cm^{-2} x sec^{-1}. The integrated flux or f l u e n c e is the time integral of flux and gives the total number of particles per cross-sectional area which penetrate a sphere of a cross-section of 1 cm^2. Frequently, for neutron fluence the term n•v•t (neutrons, velocity, time) is used. The dimension of fluence is n x cm^{-2}.

2.2 Gamma Radiation

During a radioactive decay process of an atom energy may also be emitted in the form of electromagnetic waves. The corresponding radiation which is physically similar to x-rays and light is called gamma radiation.

In addition to primary gamma radiation also secondary gamma radiation may occur as a consequence of other nuclear reactions. E.g. gamma radiation may be emitted if a neutron is captured by another nucleus so that another neutron may leave the atom thus exciting the nucleus. As a consequence the absorbed energy will be emitted in the form of gamma radiation.

To describe the energy of gamma radiation two units are frequently used: the *energy dose* is the total gamma radiation energy which is absorbed by a unit mass. It may be expressed in terms of rad (rd) which corresponds to 1oo erg/g. The second term, *dose rate* corresponds to the energy dose per unit of time and is described by rd/h or rd/sec.

3. EFFECTS OF RADIATION ON THE PROPERTIES OF SHIELDING MATERIALS

3.1 Influence on Materials Structure and Secondary Effects

Nuclear radiation may influence structural and mechanical properties of materials significantly: If in crystalline materials nuclear radiation collides with a single atom in the crystal structure the atom may be ejected from its equilibrium lattice site to a new position thus causing a lattice defect. As a consequence the material becomes more brittle. In polymers energy supplied by nuclear radiation leads to the formation of additional cross-links and thus to embrittlement of the material. Ionized rays may cause the decay of free or bonded water leading to the formation of H_2 and O_2. Finally radiation may lead to the break down of atomic bonds.

As already stated shielding of neutron radiation may cause secondary gamma radiation. Finally material may become radioactive as a consequence of exposure to nuclear radiation.

3.2 Development of Heat

It is of particular relevance for the topic treated herein that in the shielding of nuclear radiation, radiation energy is transformed into heat. Therefore, shielding of nuclear radiation always leads to a temperature increase in the shielding material. In some of the investigations summarized in the following radiation led to an increase of temperature of the concrete up to 25o^{o}C. Such a temperature increase may cause considerable damage of the concrete even if there is no radiation effect. Fig. 1 is taken from a literature review (7) on the effect of elevated temperatures on mechanical properties of concrete. It shows that sustained temperature exposure of concrete above 1oo^{o}C may cause a significant reduction of concrete compressive strength. However, the test result vary over a wide range and depend on the type of concrete making materials, moisture conditions and test methods.

The effect of temperature is even more pronounced on the tensile strength of concrete. A temperature increase from 2o to 1oo^{o}C may cause a reduction of the tensile strength of concrete by as much as 5o percent even if shrinkage effects are excluded (21).

Exposure of concrete to cyclic temperature changes as they may be expected in concrete nuclear reactor vessels are of particular significance. Already five temperature cycles between 2o and 15o^{o}C may lead to a decisive strength loss if the concrete is in a moist state during temperature exposure (3).

Because of these temperature effects in radiation experiments on concrete, frequently the specimens were cooled during radiation exposure. In some experiments the temperature effect was studied on companion specimens which were exposed to elevated temperatures, however not to radiation. Nevertheless, in many cases it is difficult to separate both effects.

4. THE EFFECT OF NUCLEAR RADIATION ON THE MECHANICAL PROPERTIES OF CONCRETE

4.1 Introduction

In the literature 3o publications could be found which deal with the effect of nuclear radiation on concrete properties. However, only 25 of those contained experimental data which were useful. In some of these papers results have been reported which had been published elsewhere so that the actual number of experimental data which can be used in the following evaluation is limited. The reason for this is not the lack of interest in such data but rather the technical and experimental difficulties encountered in performing radiation damage experiments.

In many instances comparison of experimental data from different test series is difficult because of differences in concrete making materials, mix proportions, specimen size, temperature, cooling and drying conditions. Insome instances the specimens were not cooled during radiation, and the temperature effect was not studied on companion specimens. Some of the scatter of experimental data may, therefore, be traced back to problems in comparing data from different test series and to experimental deficiencies which are, however, very difficult to avoid.

4.2 Effect of Neutron Radiation on Concrete Strength

4.2.1 Concrete Compressive Strength

Fig. 2 shows the compressive strength of concrete samples, f_{cu}, from various test series as a fraction of the compressive strength of companion specimens, f_{cuo}, which were neither irradiated nor temperature exposed (1, 2, 13, 14, 22, 28, 31). In Fig. 3 the same strength values are presented, however, the concrete compressive strength is related to the strength of companion specimens, f_{cuT}, which were not irradiated, however, temperature exposed. From Figs. 2 and 3 it may be concluded that some concretes can resist neutron radiation of more than $5 \times 1o^{19}$ n/cm^2 without a strength loss while others exhibit a strength loss at a considerably smaller radiation dose. As an average a neutron fluence of more than $1 \times 1o^{19}$ n/cm^2 leads to a marked decrease of the compressive strength of concrete. However, also for a neutron fluence of less than $1 \times 1o^{19}$ n/cm^2 the strength ratios may be < 1. Comparison of the Figs. 2 and 3 indicates that the observed strength loss is primarily due to neutron radiation though some detrimental effect of the temperature increase during radiation is apparent.

The experimental data vary over a wide range even for a given neutron fluence. For a neutron fluence of 5 x 10^{19} n/cm^2 the strength ratios range from $0.72 < f_{cu}/f_{cuo} < 1.05$ and $0.65 < f_{cu}/f_{cuT} < 1.05$. The cause of this significant scatter of experimental data as well as the parameters which affect the resistance of concrete against neutron radiation will be treated in more detail in section 4.2.3.

An investigation conducted at the ORNL graphite reactor is of some significance (4). After 12 years of service of the reactor concrete cores were taken from the biological shield. The compressive strength of these cores as a fraction of the strength of cores taken 8 years earlier is shown in Fig. 4 as a function of the distance of the location of the cores from the exposed surface of the shield. Fig. 4 clearly shows that with decreasing distance from the exposed surface the strength of concrete cores decreased and reached a minimum value of 60 percent of the initial strength of the concrete. At the time the cores were taken the maximum radiation dose to which the shield was exposed amounted to:

slow neutrons: 1.9 x 10^{19} n/cm^2

fast neutrons: 2.5 x 11^{7} rd

gamma radiation: 2.5 x 10^{19} rd

In evaluating these results is should be taken into account that the biological shield was subjected to an average temperature gradient ranging from 20°C at the outer surface and up to 40°C at the exposed inner surface. The maximum temperature during operation of the reactor ranged from 28°C to 40°C. It is likely that the shield contained little reinforcement. Thus it is possible that the observed strength decrease was not only due to radiation but also due to temperature stresses as a consequence of the temperature gradient.

4.2.2 Concrete Tensile Strength

The effect of neutron radiation on the tensile strength, f_{ru}, of concrete samples is shown in Figs. 5 and 6 (2, 14, 20). Fig. 5 gives the tensile strength of concrete samples after neutron radiation as a fraction of the tensile strength of companion specimens, f_{ruo}, which were neither irradiated nor temperature exposed, whereas in Fig. 6 the tensile strength is related to the strength of non-irradiated, however, temperature exposed specimens, f_{ruT}. According to Fig. 5 neutron radiation with a fluence of more than 1 x 10^{19} n/cm^2 may lead to a marked decrease of concrete tensile strength. Comparison of Figs. 5 and 6 indicates that temperature exposure is not solely responsible for the strength loss so that neutron radiation has caused a considerable part of the observed strength reduction. As already reported for the compressive strength also for the tensile strength the individual strength