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# The Effects of Nuclear Radiation on the Mechanical Properties of Concrete

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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 $1 \times 10^{19}$ 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 flux 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 $cm^{-2} \times sec^{-1}$. The integrated flux or fluence 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 $n \times cm^{-2}$.

### 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°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°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°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°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 $1o^{19}$ $n/cm^2$ the strength ratios range from $o.72 < f_{cu}/f_{cuo} < 1.o5$ and $o.65 < f_{cu}/f_{cuT} < 1.o5$. 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). After12 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 6o 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 $1o^{19}$ $n/cm^2$ |
| fast neutrons: | 2.5 x $11^7$ rd |
| gamma radiation: | 2.5 x $1o^{19}$ rd |

In evaluating these results is should be taken into account that the biological shield was subjected to an average temperature gradient ranging from 2o°C at the outer surface and up to 4o°C at the exposed inner surface. The maximum temperature during operation of the reactor ranged from 28°C to 4o°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, 2o). 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 $1o^{19}$ $n/cm^2$ 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 values vary over a wide range: for a neutron fluence of $5 \times 1o^{19}$ n/cm$^2$ the observed strength ratios range between the following limits: $o.2o < f_{ru}/f_{ruo} < o.82$ and $o.33 < f_{ru}/f_{ruT} < o.98$.

### 4.2.3 Parameters which Influence the Resistance of Concrete against Nuclear Radiation

The large scatter observed in the experimentel data reported sofar can with all likelihood be attributed to differences in the composition of the concrete samples, in the concrete making materials and in test procedures. In the following sections an attempt will be made to analyze the effect of these parameters.

4.2.3.1 Slow and fast neutrons--In the various investigations reported sofar slow as well as fast neutrons have been employed. Therefore, in Figs. 2 through 6 different symbols representing the test data have been used depending on the type of neutron radiation: filled symbols for slow neutrons, empty symbols for fast neutrons, and half-filled symbols where no separation between fast and slow neutrons was possible.

Is was generally expected that fast neutron radiation would lead to a more pronounced radiation damage than slow neutrons. However, this is not supported by the data given in Figs. 2 through 6. In contrast to this test data reported in (27) show that all other parameters being equal fast neutrons are indeed more detrimental than slow neutrons.

4.2.3.2 Type of aggregates--Radiation experiments in which the type of aggregate was varied are reported in (1, 2o, 22). All investigators came to the conclusion that different types of aggregates lead to concrete with different resistance against neutron radiation. In (22) mortar specimens made with different aggregates showed the following strength ratios after exposure to a neutron radiation of $8 \times 1o^{19}$ n/cm$^2$.

| Type of aggregate | Strength ratio $f_{cu}/f_{cuo}$ |
|---|---|
| Baryte | o.69 |
| Magnetite | o.78 |
| Hollith (light weight aggregate) | 1.oo |

In (2o) it was reported that the resistance of a particular type of aggregate against neutron radiation can be related to volume changes of the aggregate and the concrete during radiation. This observation will be delt with in more detail in sections 4.4.1 and 4.7.1.

4.2.3.3 Mix proportions and type of cement--In (2) the flexural strength of mortar specimens made of different mix proportions was determined after neutron exposure. The experiments indicate that the lean mixes were less radiation resistant than the rich mixes. However, it was shown that damage had been caused primarily by the temperature exposure. No further experiments are available on the effect of mix proportions on the resistance of concrete against neutron radiation.

In (22) radiation experiments were conducted on mortar samples wich were either made of portland cement or of blast furnace slag cement. After neutron radiation of 8 x $1o^{19}$ n/$cm^2$ the strength ratio for the portland cement samples amounted to o.69 whereas a value of 1.o was obtained for the samples made of blast furnace slag cement. Further experiments on the effect of type of cement are reported in (1). However the scatter of experimental data is so large that no conclusions can be drawn from these data.

### 4.3 Effect of Gamma Radiation on Concrete Strength

During the tests in which the effect of neutron radiation was studied the concrete samples were also exposed to primary and secondary gamma radiation. Unfortunately, only a few of the experimentors report the gamma radiation dose. According to (2o, 27) the gamma radiation dose during radiation exposure was as large as 3 x $1o^{11}$ rd.

Studies of the effect of gamma radiation without simultaneous exposure to neutron radiation are reported in (1, 2o, 3o). Compressive as well as tensile strength tests were carried out. The obtained test results are summarized in Fig. 7. Particularly the data from (3o) show a decrease of concrete strength with increasing gamma radiation dose.

However, these results should be evaluated with some caution: In the test series reported in (3o) the concrete samples were placed in open tin cans. The rediated specimens as well as the non-irradiated companion specimens were then placed in demineralized water which shielded the specimens against neutron radiation. Thus all concrete samples were in immediate contact with demineralized water. After several years of exposure the surfaces of the irradiated samples were partially destroyed whereas the non-irradiated samples did not show such damage. It is generally known that demineralized water may cause concrete deterioration. This is underlined by the observation that also the compressive strength of the non-irradiated companion specimens decreased significantly with time. The present test results therefore only allow the conclusion that the simultaneous effect of demineralized water and gamma radiation leads to a more pronounced deterioration of concrete than only exposure to demineralized water.

Particularly, when taking into account the results from radiation tests with simultaneaous neutron and gamma exposure it is unlikely that under normal conditions gamma radiation could have such a detrimental effect as shown by the experiments reported in (3o).

### 4.4 Load Independent Deformations

### 4.4.1 Shrinkage, Swelling and Weight Loss

In six papers it is reported that concrete undergoes a considerable volume increase when exposed to neutron radiation with a fluence of more than $1o^{19}$ n/$cm^2$. The magnitude of the volume increase depends on the particular type of aggregate used (8, 14, 2o, 24, 27, 29). In Fig. 8 the relation between volume change and neutron fluence for concrete made of limestone aggregate and of flint aggregate is shown (2o). The concrete made with flint aggregate shows considerably larger volume changes than the concrete made with limestone aggregates. Also the tensile strength of those two types of concrete are different as can be seen from the following table.

| Type of aggregate | Neutron fluence n/$cm^2$ | $f_{ru}/f_{ruo}$ |
|---|---|---|
| flint | $2 \times 1o^{19}$ | o.44 |
| | $3 \times 1o^{19}$ | o.33 |
| | $4 \times 1o^{19}$ | o.33 |
| limestone | $2 \times 1o^{19}$ | o.69 |
| | $3 \times 1o^{19}$ | o.48 |
| | $4 \times 1o^{19}$ | o.43 |

Thus it can be concluded that concrete strength is the lower the larger the volume increase during neutron radiation. In section 4.7.1 it will be shown that similar observations were made for irradiated aggregates. It is of particular significance that concrete specimens which were only temperature exposed, however not irradiated do not show such a volume increase but rather the expected shrinkage. According to (8, 31) a neutron fluence of less than $1 \times 1o^{19}$ does not lead to a volume increase of the irradiated samples. In this range the volume change of irradiated samples is approximately equal to the shrinkage of temperature exposed specimens.

Concrete samples which were allowed to dry during radiation showed a marked weight loss. Inaddition to the weight loss due to drying also gas generation was observed (14, 2o, 24). According to (2o) the components of the gas were primarily H, O, N, Co and $CO_2$. This gas generation is due to radiolysis of the water evaporating from the concrete during drying at higher temperatures. According to (14) not all of the water loss by the concrete contributes to the generation of gas.

The gas development has little effect on the concrete properties after radiation. However, it may have to be taken into account because of its possible corosive effects on other parts in a reactor pressure vessel. Furthermore, internal pressure may be developed.

### 4.4.2 Thermal Expansion

Several investigators found that for a neutron fluence up to $5 \times 1o^{19}$ n/$cm^2$ there is no significant difference between the coefficient of thermal expansion of temperature exposed samples and of neutron irradiated samples (8, 1o, 13, 17, 2o, 24). The effect of neutron radiation with a fluence $> 5 \times 10^{19}$ n/cm$^2$ as well as the effect of gamma radiation on the coefficient of thermal expansion have not been investigated.

## 4.5 Load Dependent Deformations

### 4.5.1 Modulus of Elasticity

Fig. 9 shows the effect of neutron radiation on the modulus of elasticity of concrete. There, the modulus of elasticity of irradiated concrete, $E_c$, is given as a fraction of the modulus of elasticity of companion specimens, $E_{co}$, which were neither irradiated nor temperature exposed. In this figure results reported in (1, 13, 20, 22, 29, 31) are summarized. A neutron fluence $< 1 \times 10^{19}$ n/cm$^2$ leads to a slight decrease of the modulus of elasticity compared to the modulus of untreated companion specimens. However, this decrease is with all likelihood due to the simultaneous temperature exposure. With increasing neutron fluence the modulus of elasticity of the concrete further decreases.

The available experimental data are not sufficient to separate the effects of radiation and temperature. No data are available on the influence of gamma radiation on the modulus of elasticity of irradiated concrete.

### 4.5.2 Creep

Only one series of experiments could be found in which the influence of neutron radiation on creep of cement mortar specimens was studied (20). However no final conclusions can be drawn from these tests. Nevertheless on the basis of these data it is unlikely that at least for a low neutron fluence there is a substantial difference in creep properties between irradiated and temperature exposed concrete. However it is likely that a neutron fluence which leads to a marked reduction of concrete strength will also cause an increased creep rate.

In Fig. 10 creep and shrinkage strains of sealed concrete samples while exposed to gamma radiation are shown. According to this diagram the creep strain of irradiated samples is somewhat less than that of non-irradiated specimens whereas the shrinkage strain of the irradiated and sealed samples is larger than that of the non-irradiated companion specimens. In the evaluation of these experimental data it should be taken into account that the gamma radiation dose is small so that it would not lead to any change in concrete strength. No data are available for prolonged exposure of concrete to gamma radiation.

## 4.6 Thermal Conductivity

Several reports contain data on the effect of radiation on thermal conductivity on concrete (8, 10, 13, 17, 20, 14). The results reported in (20) are shown in Fig. 11. There, the thermal conductivity, $K_c$, of irradiated samples as a fraction of the thermal conductivity of non-irradiated companion specimens, $K_{co}$, is given as a function of the neutron fluence to which the concrete was exposed. According to this figure thermal conductivity decreases as a consequence of the prevailing exposure conditions. Similar data were reported in (13) and are summarized in the following table.

| Treatment of specimen | Relative thermal conductivity |
|---|---|
| unheated | 1.oo |
| heated | o.8o5 |
| irradiated | o.77o |

All investigatores who studied the effect of neutron radiation on thermal conductivity agree in the observation that the thermal conductivity of irradiated specimens decreases by 2o to 5o percent compared to the values observed on untreated companion specimens. However, this decrease is primarily due to the effect of temperature exposure.

## 4.7 The Effect of Radiation on Properties of the Concrete Components

Several investigators conducted radiation experiments on aggregate samples as well as on neat cement paste samples (14, 2o, 24, 27, 29). The primary purpose of these studies was to clarify the question whether the influence of radiation on concrete properties can be traced back to changes in the aggregates or to changes in the cement paste. Furthermore, such studies may facilitate the choice of types of aggregates and of cement which will lead to a concrete with high resistance to nuclear radiation.

### 4.7.1 Studies on Aggregates

Several experimentors showed that aggregates undergo a considerable volume increase as a consequence of nuclear radiation (14, 2o, 24). In Fig. 12 the volume changes of serpentine aggregate and neat cement paste made from high alumina cement are shown as a function of the neutron fluence. The same diagram also shows the volume change of both components under normal temperature and at elevated temperatures without radiation (14).

According to (2o) the extent of volume increase of aggregates depends on the particular type of aggregates. Even for aggregates with similar chemical composition different volume changes may be observed depending on their microstructure (2o).

All investigators came to the conclusion that the volume increase of aggregates during radiation is the primary source for the volume increase of irradiated concrete samples as described in section 4.4.1 and shown in Fig. 8. This conclusion is underlined by the observation that in quartz aggregates the lattice parameter increases due to nuclear radiation and thus leads to the observed volume increase (27).

In addition to the volume increase of the aggregates, a decrease of tensile and compressive strength as well as of the modulus of elasticity of the aggregates was observed (14, 2o, 24). It is likely that these changes in mechanical properties are caused by the same structural changes of the aggregates which caused the volume increase as described above.

### 4.7.2 Studies on Neat Cement Paste Samples

In (14) tests on cement paste samples are reported which were made of high alumina cement. In (2o, 24) tests on portland cement paste samples are described. All investigators observed that the cement paste samples exhibit shrinkage strains when exposed to neutron radiation which are identical to the shrinkage strains of temperature exposed samples. This can also be seen from the experiments shown in Fig. 12. According to (2o)the volume decrease of the cement paste samples is proportional to the simultaneously occuring weight loss. Tensile and compressive strength as well as the modulus of elasticity of the cement paste samples change little as a consequence of nuclear radiation.

### 4.8 Relaxation Length and Shielding Properties

The relaxation length is a measure of the effectiveness of a material as a shield against nuclear radiation. It is defined as the distance from the exposed surface of the material at which the radiation dose is decreased by a factor of 1/e.

In (4) measurements of relaxation length of concrete cores taken from the ORNL graphite reactor after 12 years of service are reported. Depending on the distance from the exposed surface the relaxation length for gamma radiation varied between 13.5 cm and 14.6 cm. The relaxation length for fast neutrons varied between 1o cm and 1o.6 cm. Unfortunately, the relaxation length of this particular concrete prior to radiation exposure is not known so that the effect of radiation on the relaxation length cannot be deduced directly from these data. However the values for the relaxation length of concrete given in (4) are of the same order of magnitude as reported for non-irradiated concrete (32). Furthermore, it is unlikely that the relaxation length of concrete is significantly changed by nuclear radiation since density of the concrete as well as chemical composition are hardly altered by radiation. However, the temperature increase due to radiation will lead to a moisture loss of the concrete which in turn will cause an increase of the relaxation length for shielding against neutron radiation. This increase also will have to be taken into account when evaluating the effectiveness of a particular concrete shield.

## 5. SIGNIFICANCE OF RESULTS FROM RADIATION STUDIES ON CONCRETE

### 5.1 Summary of Experimental Data

The experimental data reported in the previous sections may be summarized as follows:

(1) For some concretes neutron radiation of more than $1 \times 1o^{19}$ $n/cm^2$ may cause some reduction of compressive and tensile strength.

(2) The decrease of tensile strength due to neutron radiation is more pronounced than the decrease of compressive strength.

(3) The resistance of concrete against neutron radiation also depends on the type of neutrons (slow or fast). However, the extent of this effect is not sufficiently clarified.

(4) The resistance of concrete against neutron radiation depends on mix proportions, type of cement and type of aggregates.

(5) The effect of gamma radiation on the mechanical properties of concrete, particularly the energy dose above which such effects are noticable is not sufficiently clarified.

(6) It is likely that the deterioration of mechanical properties of concrete when exposed to neutron radiation is in part due to the simultaneous temperature increase of the concrete. However this effect is comparatively small.

(7) The coefficients of thermal expansion and thermal conductivity of radiated concrete differ little from those of temperature exposed concrete.

(8) The modulus of elasticity of concrete when exposed to neutron radiation decreases with increasing neutron fluence.

(9) For a comparatively low radiation dose creep of concrete is little affected by radiation. It is likely that creep increases when the radiation dose is high enough to cause a reduction of compressive and tensile strength of the concrete.

(1o) For some concretes neutron radiation with a fluence of more than $1 \times 1o^{19}$ n/$cm^2$ causes a marked volume increase of the concrete. This volume increase can be traced back to microstructural changes in the crystalline aggregates of the concrete and is with all likelihood responsible for the concrete deterioration.

(11) The available test results do not allow recommendations regarding mix proportions and types of cement for concrete with high radiation resistance. However, it seems to be certain that concrete made with radiation resistant aggregates is also radiation resistant.

(12) Nuclear radiation seems to have little effect on the relaxation length and thus on the shielding properties of concrete beyond the effect of moisture loss due to the temperature increase.

## 5.2 Exposure Conditions of Relevant Concrete Structures

In order to evaluate the significance of the observations summarized in the preceding section it is necessary to estimate the radiation dose to which concrete structures may be exposed.

Sofar, radiation resistance of the concrete may be of significance in two types of structures i.e. biological shields and prestressed concrete reactor vessels. In biological shields the neutron radiation fluence may exceed values of 5 x $10^{19}$ n/cm$^2$. However, since in such structures use is made primarily of the shielding effectiveness of concrete rather than of its load carrying capacity some deterioration of the concrete strength characteristics can be tolerated particularly since the shielding effectiveness of the concrete seems to be unaffected by radiation.

In a prestressed concrete reactor vessel the radiation dose after several decades of service will depend on the particular type of reactor and on its construction. In (22) the following values are given for the maximum radiation dose to which a prestressed concrete reactor vessel may be exposed after 3o years of service:

| | |
|---|---|
| thermal neutrons: | 6 x $10^{19}$ n/cm$^2$ |
| fast neutrons: | 2 to 3 x $10^{18}$ n/cm$^2$ |
| gamma radiation: | $10^{11}$ rd |

Thus in the construction of prestressed concrete reactor vessels radiation exposure may be high enough to cause some concrete deterioration and may have to be taken into account in the choice of concrete making materials and in the design of such structures.

## 6. CONCLUSIONS

(1) The mechanical properties of concrete particularly the strength characteristics may deteriorate as a consequence of nuclear radiation if the radiation dose exceeds certain limiting values.

(2) Concrete radiation resistance and thus the critical radiation dose depend on the type of concrete making materials. If radiation resistant materials, particularly resistant aggregates are used concrete of high radiation resistance can be made.

(3) The maximum radiation dose to which some concrete structures such as prestressed concrete reactor vessels are exposed after many years of service may reach critical values for some concretes. Therefore, also the radiation resistance should be taken into account when selecting concrete making materials for such structures.

(4) Because of the good shielding properties of concrete which are not affected by radiation beyond the effect of moisture loss due to a temperature increase, the radiation dose within a concrete wall decreases rapidly with increasing distance from the exposed surface. Therefore, at some distance from the exposed surface normally not exceeding about 5o cm nuclear radiation is attenuated sufficiently so that it is of no significance for the mechanical properties of the concrete. Some deterioration of concrete strength in the heavily radiated zones can easily be taken into account in the design of such concrete structures.

## 7. LIST OF REFERENCES

(1) Alexander, S.C., "Effects of Irradiation on Concrete, Final Results", Atomic Energy Research Establishment, Harwell, 34 pp., 1963.

(2) Batten, A.W.Ch., "Effect of Irradiation on the Strength of Concrete", Atomic Energy Research Establishment, Harwell, 13 pp., 196o.

(3) Bertero, V.V. and Polivka, M., "Influence of Thermal Exposures on Mechanical Characteristics of Concrete", Concrete for Nuclear Reactors, American Concrete Institute, Special Publication, SP-34, pp. 5o5-531, 1972.

(4) Blosser, T.V.; Bond, G.W.; Lee, L.A.; Morgan, D.T.; Reid, R.C.; Reynolds, A.B.; Speidel, T.O.P.; Vroom, D.W. and Welt, M.A., "A Study of the Nuclear and Physical Properties of the ORNL Graphite Reactor Shield", Oak Ridge National Laboratory, 36 pp., 1959.

(5) Browne, R.D., "The Behavior of Concrete in Reactor Vessels", Conference on Prestressed Concrete Pressure Vessels, London, 151 pp., 1967.

(6) Browne, R.D. and Blundell, R., "The Behavior of Concrete in Prestressed Concrete Vessels", First International Conference on Structural Mechanics in Reactor Technology, Nuclear Engineering and Design 2o, North-Holland Publishing Company, pp. 429-475, 1972.

(7) Campbell-Allen, D.; Low, E.W. and Roper, H., "An Investigation of the Effect of Elevated Temperatures on Concrete for Reactor Vessels", Nuclear Structural Engineering, Vol. 2, No. 4, pp. 382-388, Oct. 1965.

(8) Christiani, G.; Granata, S. and Montagnini, A., "Behavior of Plastic Mortar Samples under Temperature and Radiation Conditions", Commission of the European Communities, Luxembourg, pp. 41-53, 1972.

(9) Clark, R.G., "Radiation Damage to Concrete", U.S. Atomic Commission, 14 pp., 1958.

(1o) Crispino, E.; Granata, S. and Risoluti, P., "Behavior of Concrete in the Presence of Thermal Stresses and Radiation", 2nd Information Meeting on Prestressed Concrete Reactor Vessels and their Heat Insulation, Brüssel, 38 pp., 1969.

(11) Crispino, E.; Fizzotti, C.; Gasparini, R.; Gualtieri, G.; Montagnini, A. and Rossi, F., "Irradiation Effects on Reactor Structural Materials", Fourth United Nations International Conference on the Peaceful Uses of Atomic Energy, 22 pp., 1971.

(12) Danish Atomic Energy Commission, "Radiation Damage in Concrete - Measurements on Miniature Specimens of Cement Mortar", Communication Research Establishment Risö; Reactor Engineering Department, 1971.

(13) Dubrovskij, V.B.; Ibragimov, Sh.Sh.; Ladygin, A.Ya. and Pergamenshckik, B.K., "The Effect of Neutron Irradiation on Certain Properties of Refractory Concretes", Atomnaya Energiya 21, pp. 1o8-112, 1966.

(14) Elleuch, M.R.; Dubois, F. and Rappenau, J., "Behavior of Special Shielding Concretes and of their Constituents under Neutron Irradiation", FourthUnited Nations International Conference on the Peaceful Uses of Atomic Energy, 7 pp., 1971.

(15) Elleuch, M.R.; Dubois, F. and Rappenau, J., "Effects of Neutron Radiation on Special Concretes and their Components", American Concrete Institute, Special Publication SP-34, pp. 1o71-11o8, 1972.

(16) Elleuch, M.F. and Dubois, F., "Les Experiences d'Irradiation des Bêtons et de leurs Constituants", Commission of the European Communities, pp. 71-96, 1972.

(17) Granata, S. and Montagnini, A, "Behavior of Plastic Mortar Samples under Temperature and Radiation Conditions", Information Exchange Meeting Concerning the Results of Concrete Irradiation Programmes, 18 pp., 1971.

(18) Granata, S. and Montagnini, A, "Studies on Behavior of Concrete under Irradiation", American Concrete Institute, Special Publication SP-34, pp. 1163-1172, 1972.

(19) Grantham, W.J., "A Study of Concrete Samples taken from the Top Shield of the ORNL Graphite Reactor", Oak Ridge National Laboratory, pp. 244-246, 196o.

(2o) Gray, B.S., "The Effect of Reactor Radiation on Cements and Concrete", Commission of the European Communities, Luxembourg, pp. 17-39, 1972.

(21) Hansen, T.C. andErikson, L., "Temperature Change Effect on Behavior of Cement Paste, Mortar and Concrete under Load", Proceedings, American Concrete Institute, Vol. 63, No. 4, pp. 489-5o4, April 1966.

(22) Houben, J.A., "DeBestraling van Mortelproefstukken" (Radiation of mortar specimens), Commission of the European Communities, Brüssel, pp. 17o-183, 1969.

(23) Kelly, B.T. and Davidson, I., "Irradiation Effects on Concrete", Conference on Prestressed Concrete Pressure Vessels, London, pp. 173-175, 1967.

(24) Kelly, B.T.; Brocklehurst, J.E.; Mottershead, D.; Mrs. McNearney, S. and Davidson, I., "The Effects of Reactor Radiation on Concrete", United Kingdom Atomic Energy Authority, G.R.D., Risley, Nr. Warrington, Lancs, Nr. 8, pp. 237-265, 1968.

(25) McDowall, D.C., "The Effect of Gamma Irradiation on the Creep Properties of Concrete", Commission of the European Communities, Luxembourg, pp. 55-69, 1971.

(26) Meyer, W. and Al-Dujaili, H.K., "Radiation Effects on Concrete and Carbonate Compounds", Second Cairo Solid State Conference, Cairo, 1973.

(27) Pedersen, A., "Radiation Damage in Concrete - Measurements on Miniature Specimen of Cement Mortar", Commission of the European Communities, Luxembourg, pp. 5-16, 1971.

(28) Price, B.T.; Horton, C.C. and Spinney, K.T., "Radiation Shielding", International Series of Monograph on Nuclear Energy, Pergamon Press, New York, London, Paris, pp. 276-278, 1957.

(29) Van der Schaaf, C.F., "Effect of Heating and Radiation on some Properties of Mortar and Concrete Specimens with Different Compositions", Commission of the European Communities, Brüssel, pp. 42-71, 1967.

(3o) Sommers, J.F., "Gamma Radiation Damage of Structural Concrete Immersed in Water", Health Physics, Pergamon Press, Vol. 16, pp. 5o3-5o8, 1969.

(31) Stôces, B.; Otopal, P.; Juricka, V. and Gabriel, J., "The Effect of Radiation on the Mechanical Properties of Concrete", Ceskoslovenska Akademie, Translated from the Czech; Oak Ridge National Laboratory, Purchase Order: 34B-83481, Letter Release No.: T81, STS No.: 14o87.

(32) Walker, R.L. and Grotenhuis, M., "A Summary of Shielding Constants for Concrete", Argonne National Laboratory, USA, ANL-6443, Nov. 1961.

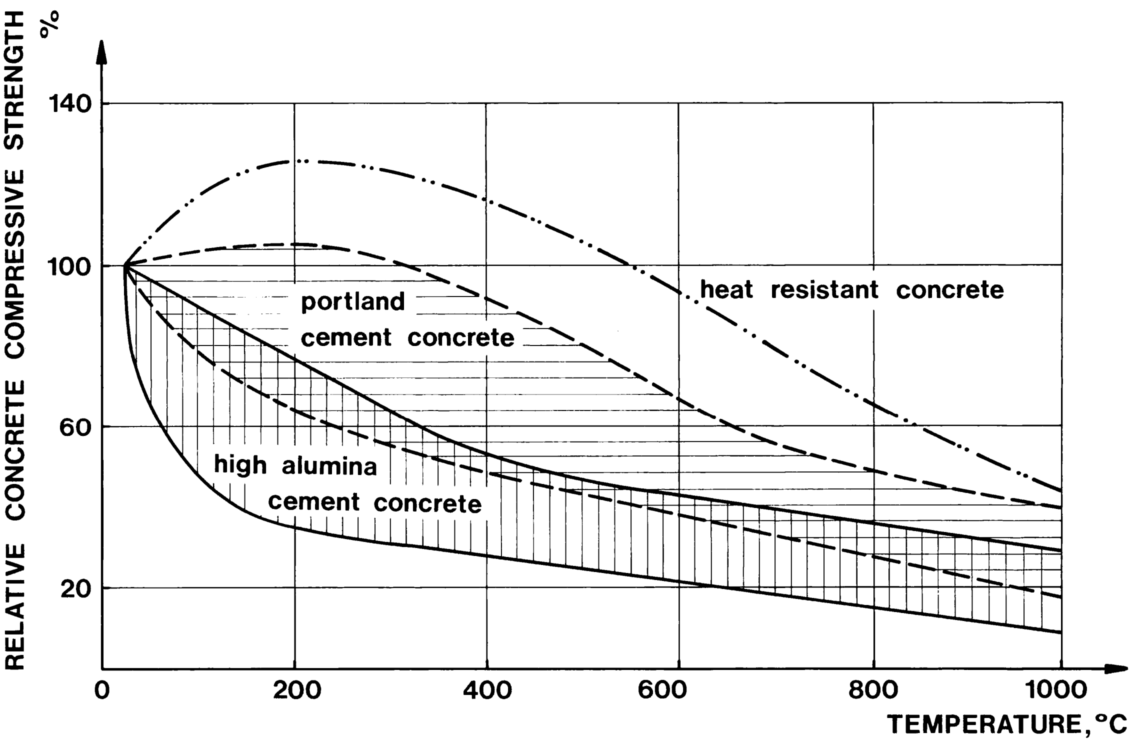

Fig. 1:
Compressive Strength of Concrete as Function of Temperature
(Campbell - Allen et. al. 7)

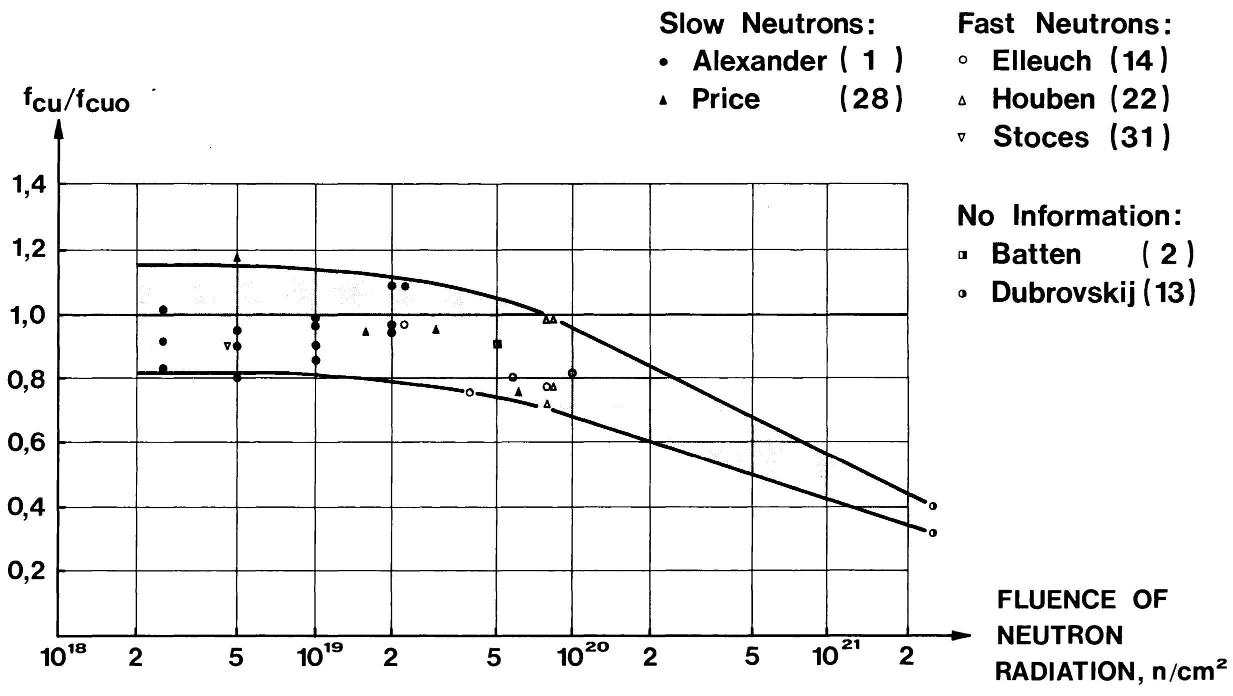

Fig. 2:
Compressive Strength of Concrete Exposed to Neutron Radiation $f_{cu}$ Related to Strength of Untreated Concrete $f_{cuo}$

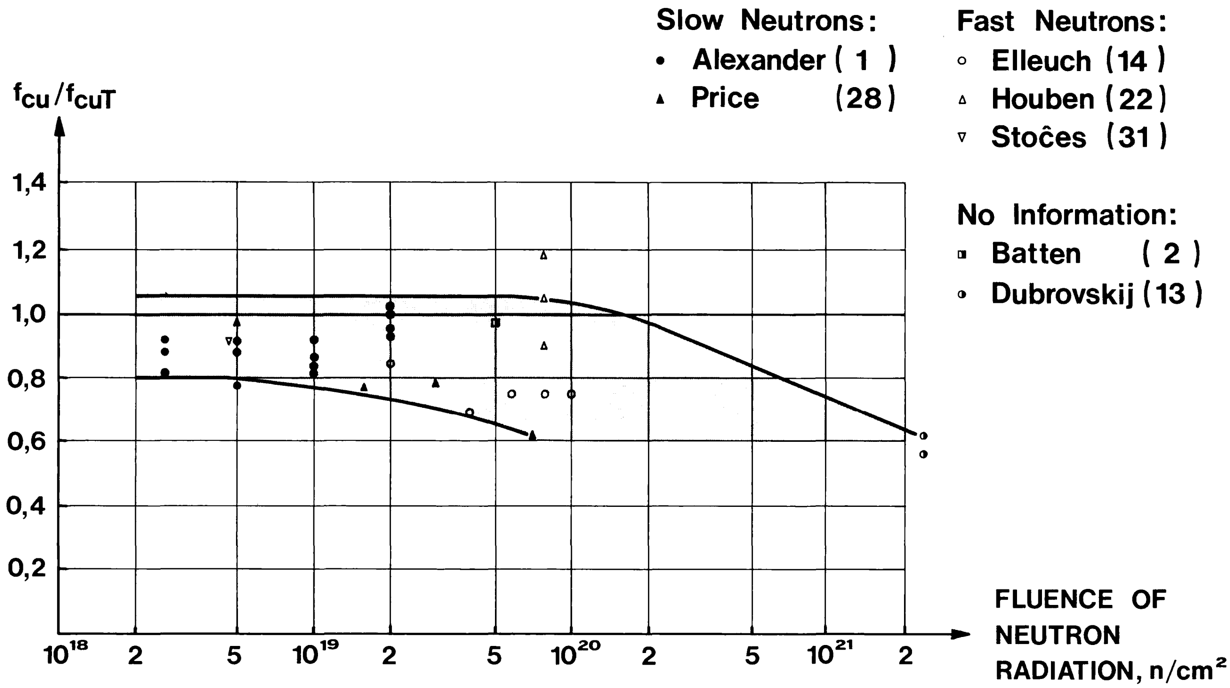

Fig. 3:
Compressive Strength of Concrete Exposed to Neutron Radiation $f_{cu}$, Related to Strength of Temperature Exposed Concrete $f_{cuT}$

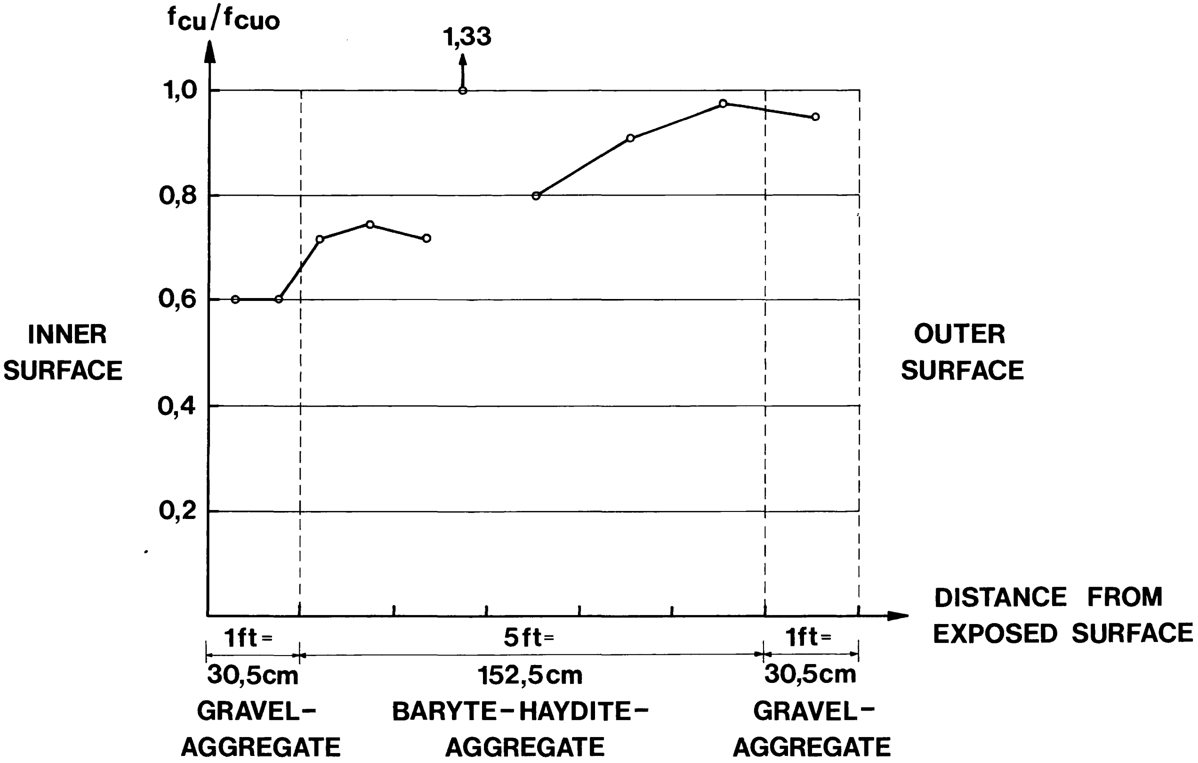

Fig. 4:
Distribution of Concrete Compressive Strength Over Thickness of Biological Shield of ORNL-Graphite Reactor (4)

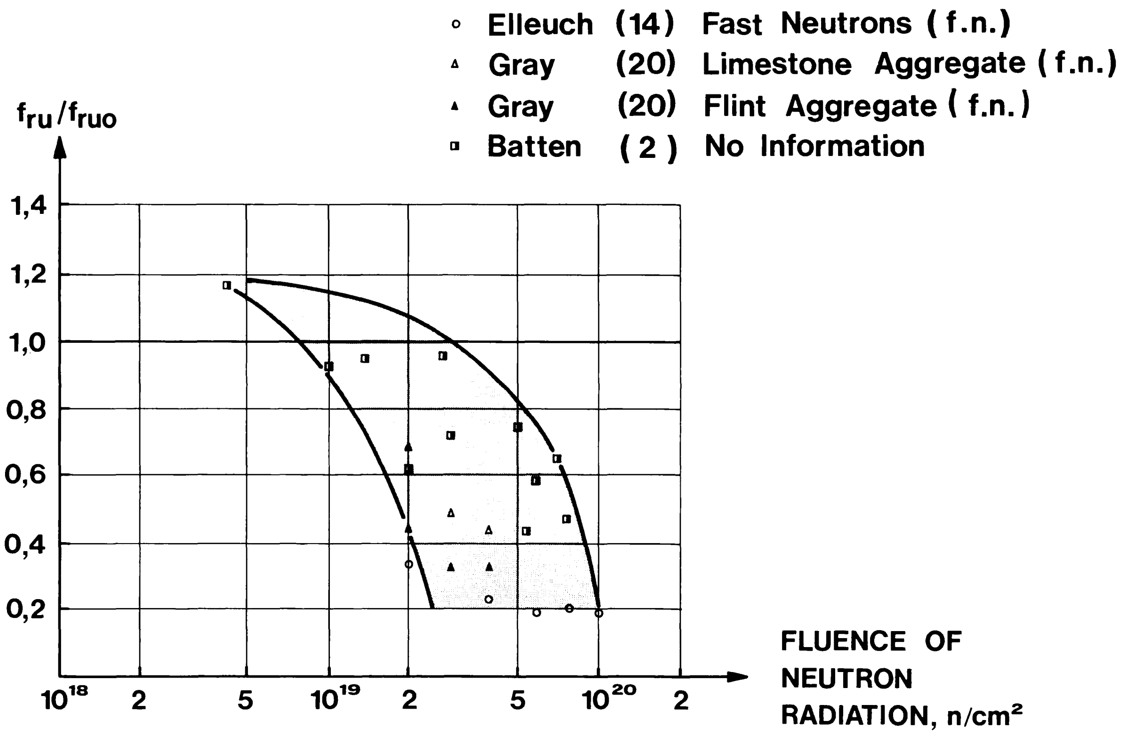

Fig. 5:
Tensile Strength of Concrete Exposed to Neutron Radiation $f_{ru}$, Related to Strength of Untreated Concrete $f_{ruo}$

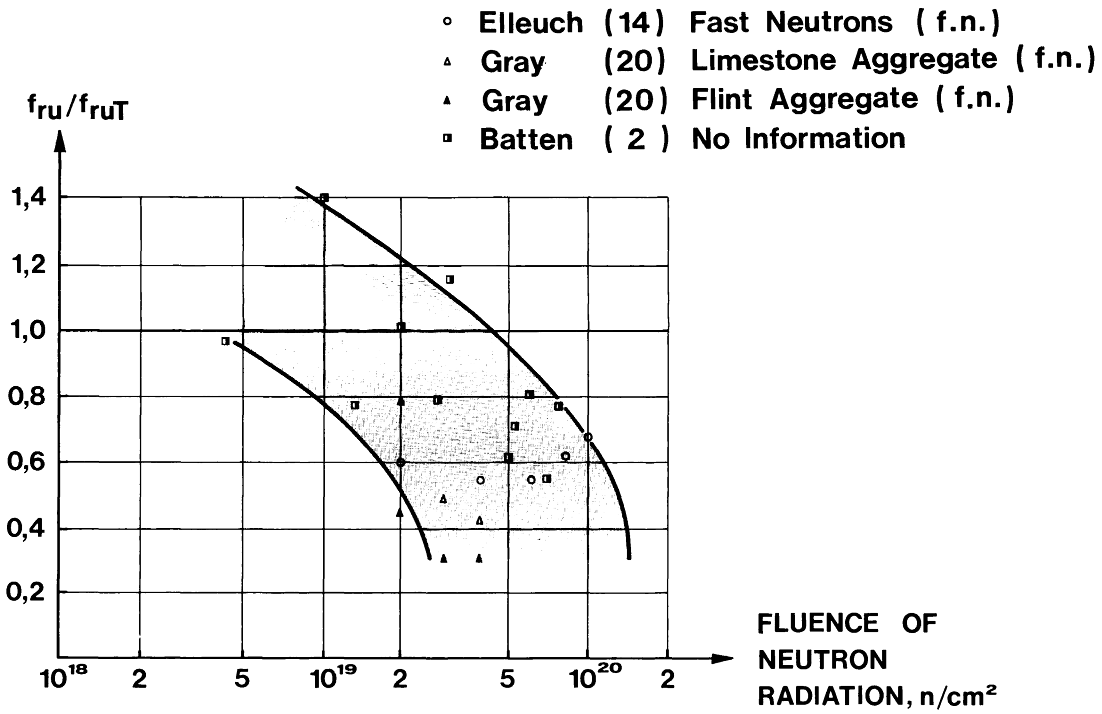

Fig. 6 :
Tensile Strength of Concrete Exposed to Neutron Radiation $f_{ru}$, Related to Strength of Temperature Exposed Concrete $f_{ruT}$

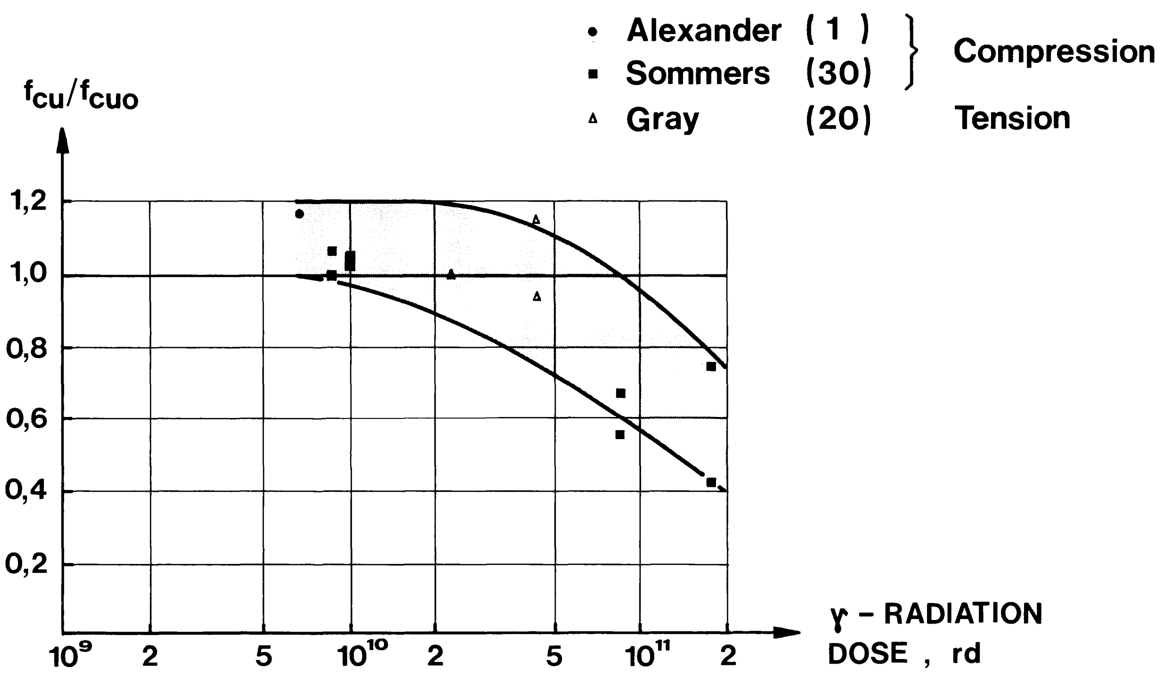

Fig. 7:
Compressive and Tensile Strength of Concrete Exposed to γ-Radiation $f_{cu}$, Related to Strength of Untreated Concrete $f_{cuo}$

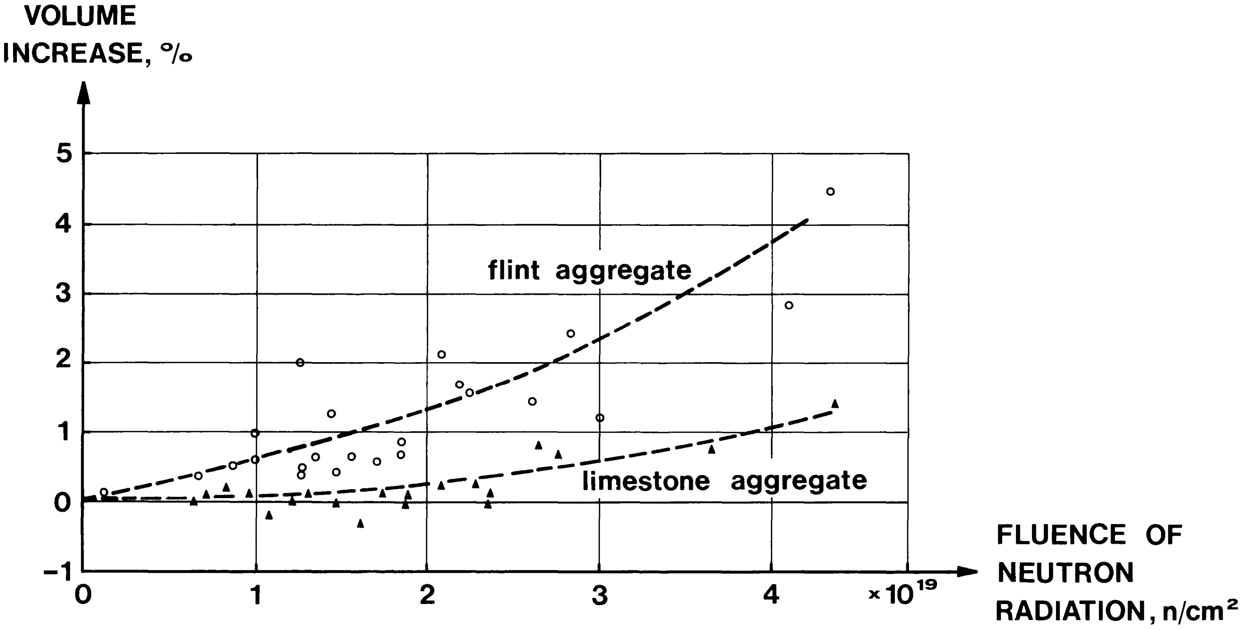

**Fig. 8:**

**Volume Change of Concrete Specimens Exposed to Fast Neutrons According to Gray (20) and Kelly et. al. (24)**

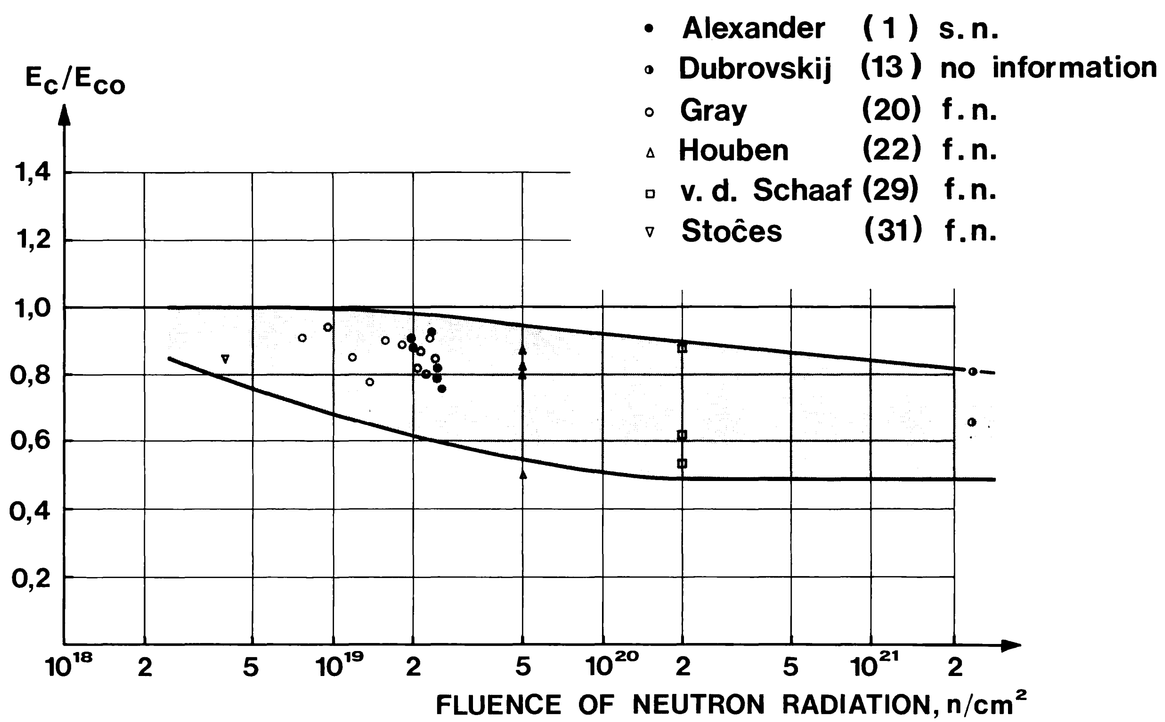

Fig. 9:
Modulus of Elasticity of Concrete After Neutron Radiation $E_c$, Related to Modulus of Elasticity of Untreated Concrete $E_{co}$

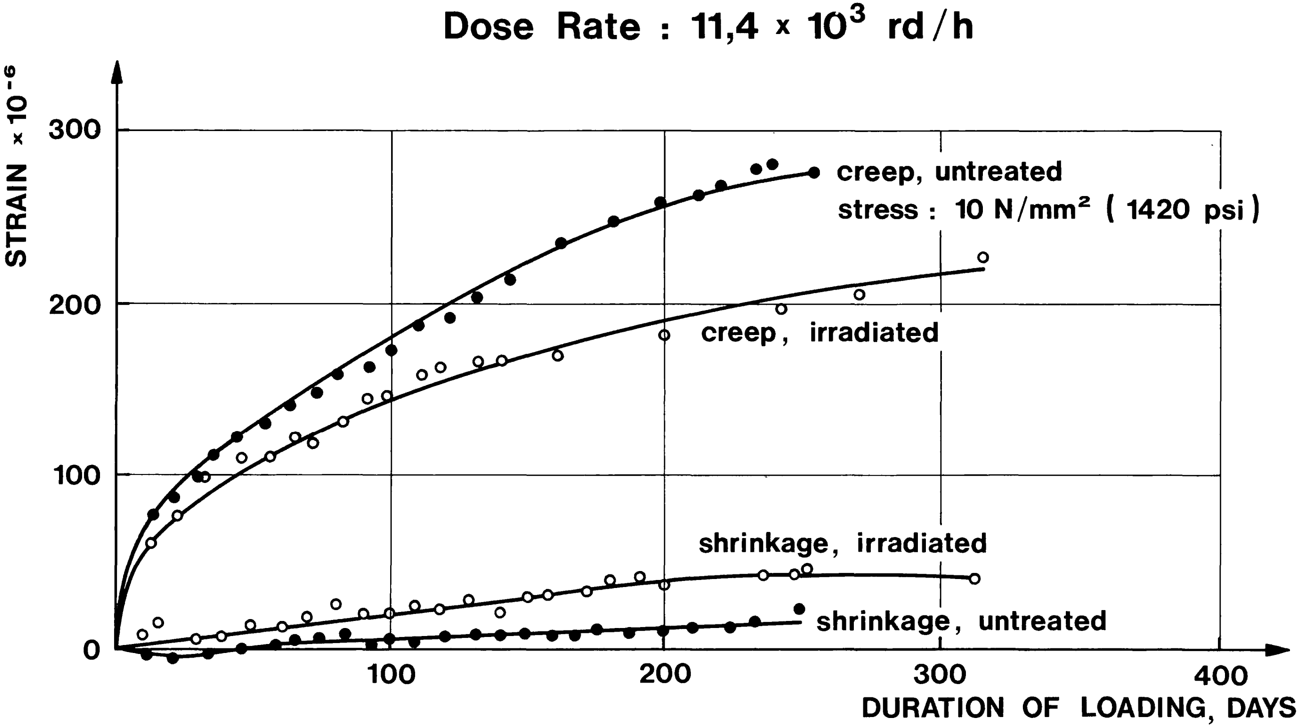

Fig. 10 :
Effect of γ - Radiation on Creep of Concrete According to Mc Dowall (25) , All Specimens Sealed

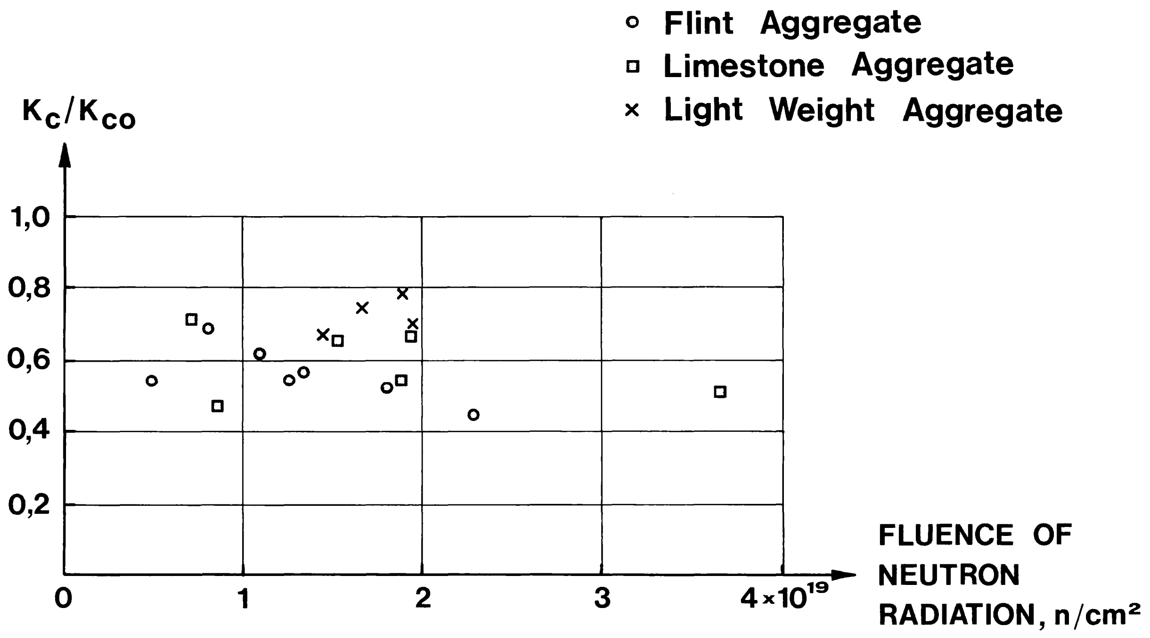

Fig. 11:
Thermal Conductivity of Concrete After Neutron Radiation $K_C$, Related to Thermal Conductivity of Untreated Concrete $K_{CO}$ (20)

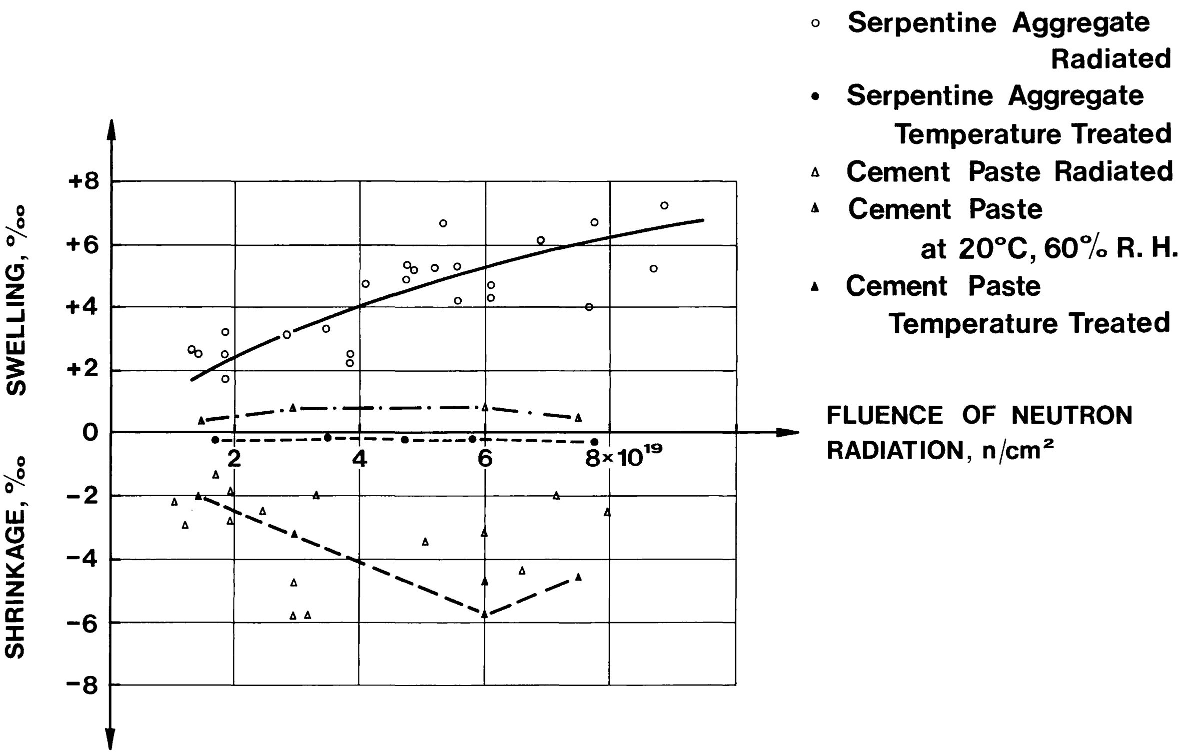

Fig. 12:
Volume Change of Aggregates and Hardened Cement Paste During Radiation with Fast Neutrons According to Elleuch et. al. (14)