Shielding Concretes for Liquid Sodium Cooled Nuclear Reactors

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ABSTRACT

Concretes with shielding properties are commonly employed in nuclear power plants and require specific technologies to determine the most suitable mixtures, in particular with respect to the high density concretes used for neutron shielding of reactor cores.

The scope of this paper is to describe the process of determination of the mixture characteristics of high density hematite concretes with special bonding agents, for use in the shielding structures of the core of high speed nuclear reactors.

In particular, the scope of the research was to develop concretes with low water loss and high strength with time during continuing operation in relatively high temperature environment.

The required physical properties of the concrete are:

- density greater than or equal to 3.8 tons per cubic meter,
- 28 days compressive strength greater than 500 kilograms per square centimeter,
- retained water at 200 degrees centigrades higher than 10 liters per cubic meter.

The optimum mixture is determined by the following processes:

- selection of materials capable of yielding concretes of the required density,
- chemical/physical analysis of the mix components,
- optimization/determination of required sieve analyses with quantitative analysis of each sieve group,
- determination of the fineness modulus drawn from the selected sieve analyses,
- preparation of various mixtures with the criteria of minimizing water content, obtaining high workability (to meet the needs of the various casting operations) and 28 days compressive strength of at least 500 kilo-

grams per square centimeter, and achieving retention of the required physical properties at 200 degrees centigrades,

- study of mixture response to variations in temperature with the scope of determining the modulus of elasticity,
- verification of mechanical properties at 20, 200 and 300 degrees centigrades.

The properties of shielding concrete obtained during the process by using different mixtures are presented, in order that the influence of the various parameters on the final properties of the concrete is identified. Particular attention is given to the evaluation of the properties of concrete subjected to thermal conditioning (200-300 C) simulating conditions during reactor operation.

1. Introduction

It is a common practice to use concrete of a specially selected composition to form a shield round the core of a nuclear reactor. This shield acts both as a thermal as well as a neutron shield. To act as a neutron shield, the concrete should contain components such as water which slows down the fast neutrons so as to facilitate their adsorption by the other components present. The other components should be chosen so that they not only adsorb the slow neutron, but also the X-ray and γ-ray photons which are produced during the slowing down of the fast neutrons e.g. hematite.

As a thermal shield, one end of it i.e. the hot end will be at a higher temperature than the other end i.e. the cold end. It is therefore desirable that the shield should have some water even at the hot end. As the temperature of the hot end can be about 200° to 300°C, the water at this end has to be in a chemically bound state which could not be lost at the operating temperature. In the case of a liquid sodium cored reactor, the concrete shield will have to satisfy a further safety requirement. In the case of accident or leakage, molten sodium at about 400°C may come into contact with this shield. Liquid sodium at this temperature is very reactive. If the chemically bound water is set free at this temperature, sodium will react exothermically with water, forming hydrogen. If the shield contains a large quantity of water, the above reaction may cause an explosion. It is obvious that the water content of the shield, especially at the hot end, has to be restricted. Besides the above characteristic water content, the concrete should contain a minimum amount of heavy aggregate such as hematite per cubic meter. It should also retain a minimum of strength at the working temperature. In addition to the above requirements in its hardened state, the concrete mix, in its fresh state, should have sufficient workability so that it could be cast easily in the required shape. It is not an easy task to find a concrete which can fulfil all the above requirements. This paper describes work done to find suitable concrete compositions for a liquid sodium cored reactor of a particular design.

2. Design requirement of the shield concrete

The design requirements of the shield concrete are as follows:

(I) hematite should constitute both the fine and coarse aggregates,

(II) the minimum acceptable density is 3.8 tons per cubic meter,

(III) at 28 days the minimum compressive strength is 500 kg/cm^2,

(IV) 28 days humid cured concrete should retain at least 10 litres of water per cubic meter when heated to 200°C,

(V) it should retain at least 400 kg/cm^2 strength when heated to 200°C.

(VI) the concrete mix in its fresh state should have a slump between 30 to 40 mm.

3. The initial considerations

Hematite is a natural rock mineral with a specific gravity of 5.2. The crushed grains of hematite are very angular and somewhat flaky in shape. In order to get a concrete of the required density the following have to be carefully regulated:

(a) grading of crushed hematite,

(b) cement and water contents.

To achieve the required retained water content at 200°C, the cement and the initial water contents have to be kept low. However, to get the required strength and slump at a low cement content, either a super-plasticizer or super-plasticized cement has to be used.

Furthermore, to retain a high proportion of the initial strength after heating to 200° to 300°C, a definite heating rate has to be worked out.

4. Selection of hematite grading, cement type, cement and water contents

From some preliminary experiments and theoretical considerations, the following three gradings of hematite were chosen for detailed investigation. It was thought desirable to have a cement content in the range of 330 - 370 kg/m^3 and a water content not higher than 170 litres. The required workability (slump) would be obtained when necessary by using a super-plasticizer.

Two cements were chosen for this investigation. One was a pozzolanic cement conforming to the italian standard specification n° 425. The other was a proprietary product "Macflow". Macflow is a mixture of a specially graded portland cement, a powdered super-plasticizer, an espansive agent and an anti-bleeding agent.

5. Experimental techniques

Hematite was obtained as crushed rock of the required grading. Before use, the individual size fractions were analyzed chemically and mineralogically. Their water adsorption capacity were also measured.

From the above materials concrete mixes were prepared. The composition of those mixes which were chosen for detailed study are shown in table 2.

From each of the mixes, sufficient numbers of prisms were cast to measure the following properties:

(I) compressive strength and dynamic modulus at 7 and 28 days,

(II) static modulus at 28 days,

(III) drying shrinkage at 20°C and 60% r.h.
The dynamic modulus was measured bv means of an ultrasonic pulse velocity technique.
In order to investigate the strength and water retention at the assumed operating temperature, some of the prisms were gradually heated to 200°C or 300°C. The strength of the heated prisms were measured either when they were substantially at 2-300°C or after slow cooling to 20°C. Parts of the crushed prisms were heated to 600°C to determine their retained water contents.

6. Results, discussions and conclusions

The chemical analyses showed that all the fractions of hematite contained in excess of 98% Fe_2O_3. The main impurities are - SiO_2 about 0.5 to 1% and alkaline - earth oxides about 0.5%. Mineralogically the fractions were hematite. The water adsorption capacity of the 0 - 0.5 mm. fraction was 3.2% and for other fractions it was about 1.2%.
An examination of tables 2 and 3 will show that by proper adjustments of hematite grading, cement type, water, cement and super-plasticizer contents, it is possible to make a concrete of density 4290 kg/m³ without any sacrifice in its workability.
Table 3 also shows the mechanical properties of hardened mixes. An examination of table 2 and 3 shows that higher strength and elastic modulii are obtained by using Macflow, than by using pozzolanic cement or a mixture of pozzolanic cement and Macflow. Note especially, that the mix nos. 15 and 21, have high densities and mechanical properties and retained only 33 and 28 liters of water per cubic meter. These low water retentions may be preferable in the particular context of their use.
One of the most important requirements of concrete for nuclear shielding is its retention of compressive strength at the operating temperature of 200° - 300°C. It is this retained strength which is important. The compressive strengths shown in table 3 though indicative are of secondary importance.
It is known from the concrete literature that the rate of heating, especially at the initial stages, is a very important parameter in determining the retained strength. Fig. 1 shows the heating schedule followed in this investigation. The heating rate never exceeded 40°C per 24 hours.
As the weight loss curve (Fig.1) shows the temperature was raised only after weight loss had attained a constant value. The reason for this slow heating was to allow vapour to diffuse out without causing an undue pressure rise inside the prisms. The retained strength are shown in table 4. From table 4 it can be seen that all the mixes, except for mix no. 15, retained their strength or improved upon it. Even mix no. 15 showed only a marginal loss at 200°C and

a marginal strength gain at 300°C. Table 4 also shows that cooling from 200°C to 20°C actually increased the strength of allthe mixes. These are very interesting and promising results. These results indicate for this type of concrete that with proper care, it is possible to improve or at least retain strength even after heating to 300°C. More importantly, these results show that at least the first cooling to 20°C may not affect the strength of heated concretes.

Fig. 2 shows the drying shrinkage values of different mixes. It is obvious that the mixes nos. 15, 16 and 21 have lower shrinkage than mixes nos. 11 and 12.

Taking all the results together it will appear that mix nos. 15 and 21 are best suited for the application under consideration.

Table I

Size distributions of hematite aggregate

Size range in mm. \ Proportioning n°	Material in kg. (fractional weight)					
	1		2		3	
0 - 0.5	570	(0.17)	367	(0.10)	356	(0.095)
1 - 1.5	704	(0.21)	1028	(0.28)	350	(0.093)
1.5 - 5	670	(0.20)	435	(0.12)	350	(0.093)
5 - 15	1408	(0.42)	1836	(0.50)	1317	(0.352)
15 - 35	--	--	--	--	1373	(0.367)

Table II

Mix composition of concrete mixes

Size range in mm. \ Mix n°	Material in kg/m³				
	11	12	15	16	21
Aggregates proportioning n°	1	1	2	2	3
Hematite	3352	3533	3666	3594	3746
Pozzolanic cement	332	--	--	178	--
Macflow	--	350	370	178	327
Water	163	137	155	165	124
Rheobuild 561	6	--	--	3.96	--

Table III

Physical properties of the concrete samples at 20 C

Property \ Mix n°	11	12	15	16	21
Slump in cm.	4	4	3.5	3.5	3
Density kg/m³	3850	4020	4192	4118	4311
* Compressive strength in kg/cm² at 7 days	333	635	656	515	726
* Compressive strength in kg/cm² at 28 days	515	897	914	708	911
Flexural strength in kg/cm² at 28 days	58.6	82	86.1	75	84
Dynamic elastic modulus in kg/cm²·10³ at 7 days	591	848	815	805	1275
Dynamic elastic modulus in kg/cm²·10³ at 28 days	663	868	885	827	1348
Static elastic modulus in kg/cm²·10³ at 28 days	381	582	542	538	705
Water/cement ratio	0.49	0.39	0.418	0.46	0.38
Water retained after heating to 200° - lt/m³	44	49	33	43	28

*Strengths were determined on 150 mm. cubes.

Table IV

Retained strength of concrete mixes

Mix n°	11	12	15	16	21
* Compressive strength at 28 days - 20°C - 90% R.H.	515 kg/cm²	897 kg/cm²	914 kg/cm²	708 kg/cm²	911 kg/cm²
* Compressive strength at 200°C	653 kg/cm²	1004 kg/cm²	831 kg/cm²	704 kg/cm²	1280 kg/cm²
* Compressive strength after cooling to 20°C	711 kg/cm²	1298 kg/cm²	1120 kg/cm²	955 kg/cm²	1300 kg/cm²
* Compressive strength at 300°C	600 kg/cm²	949 kg/cm²	1090 kg/cm²	902 kg/cm²	1262 kg/cm²

*Strengths were determined on 150 mm. cubes.

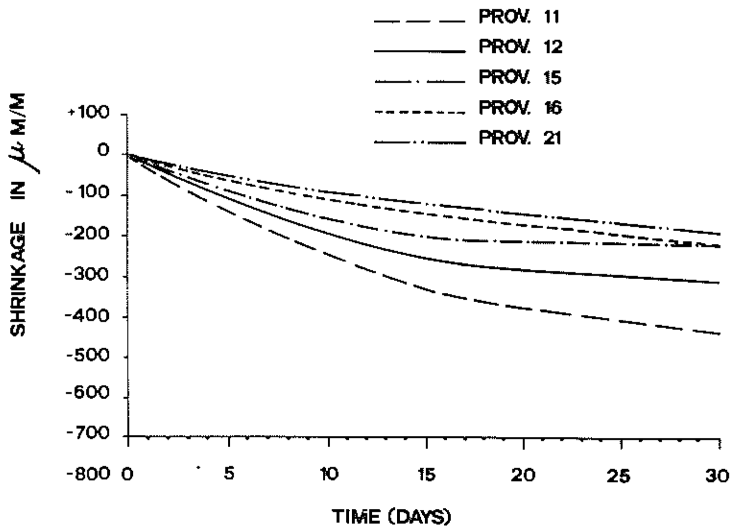

Fig. 1 Time-temperature schedule of the concrete sample.
Note: The shrinkage data was collected after 28 days humid curing and hence the initial expansion due to Macflow is lost.

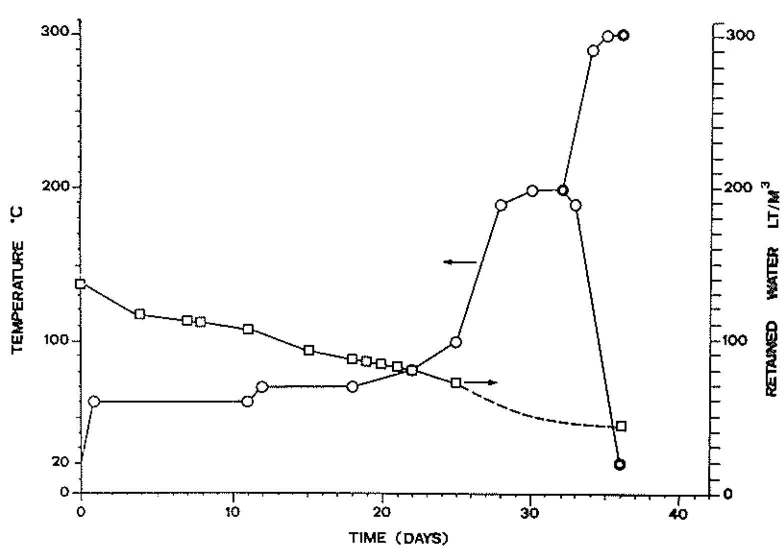

Fig. 2 Drying shrinkage of concrete samples - 20°C - 65% R.H.