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Influence of moderately elevated temperatures on engineering properties of concrete used for nuclear reactor vaults

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ABSTRACT

This paper describes the results of experimental investigations on the engineering properties of normal aggregate concrete for nuclear reactor vaults. The concrete was subjected to various moderately elevated temperatures – 65, 75, and 90 °C, as well as a thermal cycle between 43 and 90 °C – for extended periods up to 540 days, and the performance was compared to concrete cured under moist conditions at room temperature for the same duration. While the progressive removal of moisture from the concrete exposed to high temperatures reduced its stiffness, there was a marked increase in strength. Thermal cycling was seen to be the more critical exposure environment when compared to constant high temperature storage.

1. Introduction

When hardened concrete is exposed to moderately elevated temperatures, the free water in the paste starts to migrate and evaporate [1,2]. This causes an alteration of the physical and chemical structure of concrete, which modifies its behaviour. These alterations are not well understood, and the existing data show great variations due to the large number of test variables involved [1–4]. Most researchers [2–7] have reported an increase in compressive strength for longer exposure periods at temperatures less than 100 °C. Also, sealed and unsealed concrete are reported to behave differently at elevated temperatures due to the different state of water evaporation in them. For unsealed specimens, elastic modulus of concrete heated to high temperatures is reported to be reduced. It is also observed that the changes in compressive strength/modulus cease, as the moisture condition in the concrete is stabilised. The loss of moisture present in the concrete is dependent on the magnitude and duration of temperature loading. Increase/decrease in strength depends on the moisture availability and microcracking in concrete.

Bond strength is reported to be higher for deformed bars than plain bars as temperature is increased and, the bond behaviour at high temperature has significant influence on cracking and deformation capacity of concrete [8].

Elevated temperature usually accelerates the hydration process as well as the drying process, although the hydration process ceases completely in dry concrete [4]. Both of these lead to an alteration in the properties of concrete. The effect of temperature (in the range 60–100 °C) on the physical, thermal and mechanical properties of concrete have been analysed and summarised in Table 1.

From the above discussion and the information in Table 1, it can be concluded that the main factor affecting the change of concrete behaviour at temperatures up to 100 °C is the moisture content and moisture migration. Other factors are the loss of free water and changes in mass density and porosity. The water migration leads to the hydration of unhydrated cements and evaporation from pores continues until equilibrium is reached. For any further change to occur, the temperature of the system should be raised. Hence, if properly compacted, cured and dried out, concrete can resist sustained moderately elevated temperatures more effectively.

2. Research significance

Normal aggregate concrete is used in the vaults of Fast Breeder Nuclear Reactors. These are two Reinforced Cement Concrete cylindrical structures, namely, inner vault and outer vault, which support the main vessel and safety vessel. They are subjected to moderately elevated working temperatures due to the heat emitted from the main vessel as a result of the nuclear reactions. The temperature in the main vessel is of the order of 500 °C. But the temperature in the vaults is limited to 65 °C as per the recommendations in ACI 349_01/349R-01 under normal operation and 90 °C under Safety Grade Decay Heat Removal (SGDHR) conditions. It is considered that at this temperature no marked changes in concrete

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Table 1
Properties of concrete influenced by moderately elevated temperatures [1–8].

Property of concrete	Influence of temperature	Remarks
Moisture loss	High	Rate of water loss depends on W/C ratio and treatment temperature
Moisture content and moisture migration	High	Gel water migrates to capillary pores. Magnitude of moisture loss is higher for higher temperature
Mass density	High	Decrease is lower for concrete with larger aggregate and air cured specimens. Density is largely influenced by moisture content
Porosity	High	Porosity increases parabolically [1] and original pore structure is not recoverable on resaturation
Thermal expansion	Low	Expansion increases as the proportion of cement paste increases; moisture content, water–cement ratio, and cement type influence expansion at moderate temperatures
Specific heat	Low	Depends on moisture content of paste while heating
Thermal conductivity	Low	Conductivity varies linearly with moisture content; Mixes with more fines have higher conductivity and higher variation in conductivity
Compressive strength	Moderate	Strength loss/gain depends on the moisture content, mix design, maximum temperature, duration of exposure, aggregate type, curing conditions, age of concrete and testing conditions. Increase/decrease in strength depends on the moisture availability, microcracking and deformation capability of concrete
Tensile/flexural strength	Moderate	More sensitive than compressive strength and hence percentage reduction is more
Modulus of elasticity	Moderate	For normal strength concrete, elastic modulus decreases with temperature. Influenced by the type of aggregate and curing conditions
Poisson's ratio	Low	Not much influenced by moderate temperatures. Remains in the range 0.15–0.20
Creep	Moderate	Creep strains increase very rapidly until a stable moisture content is reached and is remarkably affected by highest temperature. Creep increases with increasing load level and sealing of specimens as it affects moisture transport. Water cured specimens have higher creep
Bond strength	Moderate	Ribbed bars have higher bond strength than plain bars. Bond strength depends on the cracking and deformation capability of concrete

properties will take place, apart from slow drying. The temperature is maintained at 65 °C in the vaults with the help of Biological Shield Cooling System (BSCS) and thermal insulation panels mounted on the outer surface of the safety vessel.

In order to study the effect of further increase in temperature, there is a need to carry out investigations on the influence of moderate temperatures (65–90 °C) on the engineering properties and microstructure of concrete. Increase in the permissible temperature would save energy and relax the biological cooling system around the reactor vault. Also, proper design of these structures requires a detailed knowledge of the properties of concrete at their elevated working temperature.

3. Experimental methods and materials

A commercially available 43 grade ordinary Portland cement was used for all the mixtures (equivalent to ASTM Type I or EN 197 CEM I). River sand was used as fine aggregate and crushed granite as coarse aggregate (However, the study of the effect of aggregate was not within the scope of this investigation). Potable water and a naphthalene based superplasticiser were used. The mix had a water–cement ratio of 0.36 by mass, cement content of 400 kg/m^3 and a nominal slump of 75 ± 25 mm. The average compressive strength at 28 days was 53 MPa (to satisfy the requirements of M45 concrete). These proportions were used for all of the concrete mixtures in the study (details presented in Table 2). Concrete was prepared using a drum mixer with a capacity of 100 l. A slump test was performed for checking the workability and the fresh concrete was placed in the various oiled moulds and compacted using external table vibration. The concrete specimens in the moulds were then removed after 24 h and kept in a moist room for the required curing period.

Table 2
Concrete mixture proportions (for all mixtures) used in the study.

Ingredient	Quantity
Cement	400 kg/m^3
Water	144 kg/m^3
Fine aggregate	764 kg/m^3
Coarse aggregate	1144 kg/m^3
Superplasticiser (SNF based)	2 kg/m^3 (0.5% by weight of cement)
W/C	0.36
Slump	75 ± 25 mm

After 28 days of moist curing, the specimens were taken out and wiped surface dry and were directly placed in the ovens set at the required temperatures. Five different temperature regimes i.e., control temperature (moist room 27–30 °C & relative humidity of 95%–100%), constant 65 °C, constant 75 °C, constant 90 °C and thermal cycling between 43 and 90 °C were used in this study. Three constant temperature ovens and a programmable oven were used for storing the specimens at the required temperatures. Afterwards, the changes in the compressive strength, modulus of elasticity, flexural strength and bond strength were monitored for a period of 360 days (additional tests for compressive strength at 450 and 540 days were also conducted). At the age of testing, specimens were removed from the oven, permitted to slowly cool to ambient temperature and then tested to determine residual mechanical properties. Additionally, measurements of length, mass and ultrasonic pulse velocity on 100 mm cube specimens were also carried out periodically. All the tests were performed according to the relevant IS/ASTM standards. The tests were carried out after 28, 90, 180 and 360 days of exposure for constant temperature storage and after 30, 90, 150, 210 and 300 cycles for thermal cycling specimens. Table 3 shows the testing details, in terms of the type of specimens, and the relevant standards for constant temperature storage specimens, while Table 4 shows similar details for specimens exposed to thermal cycles. The details of the thermal cycle used in the study are shown in Fig. 1. This cycle was selected as an accelerated version of the actual cycle (Fig. 2) of the reactor vault, and was vetted by personnel from the Indira Gandhi Centre for Atomic Research, Kalpakkam, India.

4. Results

4.1. Effects on physical properties of concrete

For calculating the density, measurements of mass were done periodically until an age of 360 days. Density of concrete was found to decrease for heated specimens, as expected, because of moisture

Table 3
Age of testing and specimens used for constant temperature storage.

Test	IS/ASTM code	Specimen prepared	Age of testing (in days after keeping in oven)	No. of specimens
Compressive strength	IS 516 (1959)	100 mm cubes	28, 56, 90, 180, 270, 360, 450, 540	99
Flexural strength	IS 516 (1959)	100 × 100 × 500 mm beams	28, 130, 360	26
Thermal expansion	ASTM C-490	75 × 75 × 300 mm prisms	Continuous	16
Modulus of elasticity	IS 516 (1959)	150 × 300 mm cylinders	28, 110, 210, 360	51
Pullout resistance	ASTM C-900	22 mm bars embedded in 150 mm cubes	28, 130, 180	39
Weight loss and ultrasonic pulse velocity	IS 13311: Part 1 (1992)	100 mm cubes	Continuous	12

Table 4
Age of testing and specimens used for thermal cycling.

Test	IS/ASTM code	Specimen prepared	No. of cycles exposed	No. of specimens
Compressive strength	IS 516-1959	100 mm cubes	30, 90, 150, 210, 300	15
Flexural strength	IS 516-1959	100 × 100 × 500 mm beams	60, 150, 210, 300	8
Modulus of elasticity	IS 516-1959	150 × 300 mm cylinders	30, 90, 150, 210, 300	15
Pullout resistance	ASTM C-900	22 mm bars embedded in 150 mm cubes	30, 90, 150, 210, 300	15

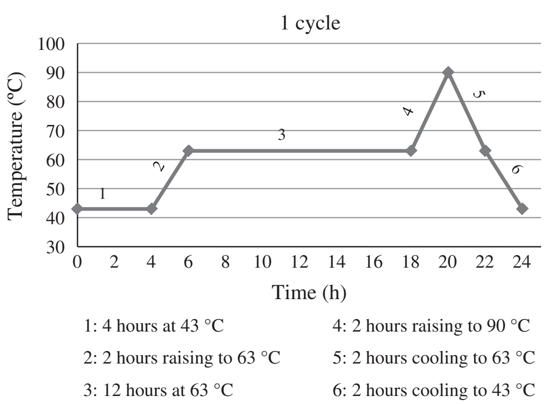

Fig. 1. Accelerated thermal cycling used in the study.

loss. The specimens kept in the moist room showed a marginal increase in density. After a period of about 50 days, no further significant changes were observed, as evident from Fig. 3. There was about a 3.1% decrease at 65 °C and a 3.5% decrease at 90 °C. Since there was no mass change for heated specimens after 50 days, the system is expected to have reached equilibrium with the driving forces.

Ultrasonic pulse velocity was found to decrease for the heated concretes, and the decrease was more for the concretes at 90 °C. There was a 20% decrease at 65 °C and a 26% decrease at 90 °C. After about 55 days of exposure, the pulse velocity values were found to stabilise, as seen in Fig. 4. This corresponds well with the stabilisation of the mass (density) of the specimens – both these factors point to the crucial role played by the moisture content of the concrete. Further, it also suggests that no additional alteration is occurring in the heat cured concretes. Comparing to the guidelines in IS 13311 Part 1 (1992), it can be concluded that the control concrete is in 'Excellent' condition, while the heated concretes are 'Good'.

The variation in dynamic modulus for the concretes stored at different temperatures is described in Fig. 5. Since the dynamic modulus is a function of the product of the square of pulse velocity and mass density, it tends to clearly show the differences in the state of deterioration of the various concretes. The pulse velocity is dependent on the density of the medium through which it travels; it travels faster in water than in air. Hence in heated concretes, the time of travel of the pulse is longer as the water present in the pores has evaporated. The first pulse to arrive at the receiving transducer will have been directed around the periphery of the pores, hence resulting in a longer time of travel. The results in the figure clearly show the detrimental effect of the higher temperatures. While there is almost no increase in the level of deterioration when the temperature is increased from 65 °C to 75 °C, a

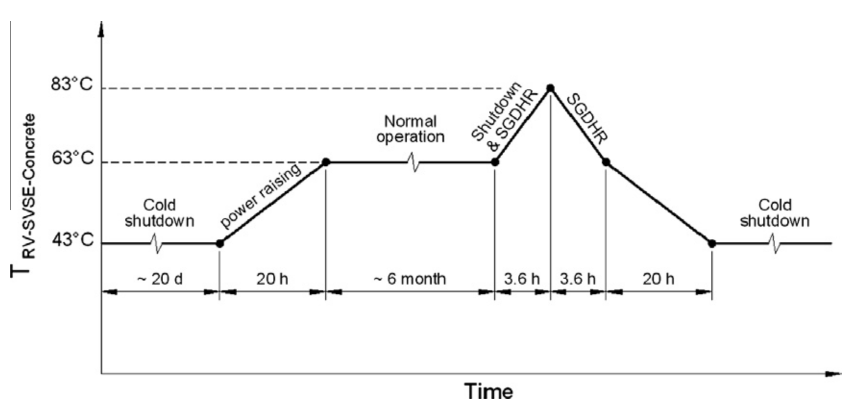

Fig. 2. Actual thermal variations in the SVSE part of the vault concrete (from IGCAR, Kalpakkam).

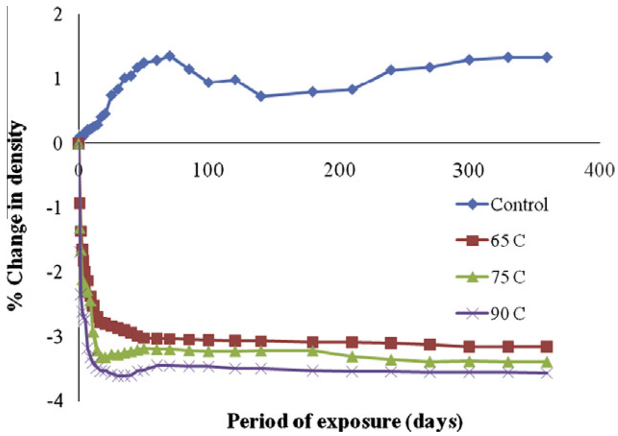

Fig. 3. Variation in density of concrete exposed to different temperatures.

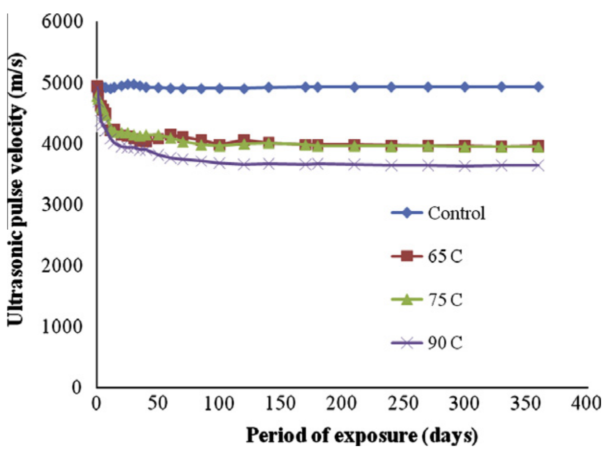

Fig. 4. Ultrasonic pulse velocity for concrete subjected to different temperatures.

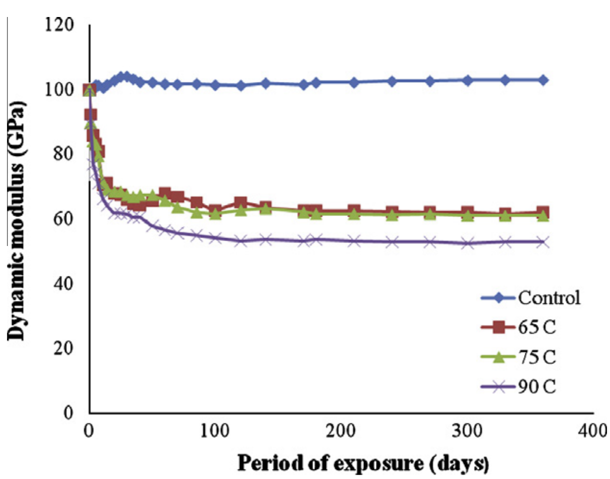

Fig. 5. Variation in dynamic modulus for concrete subjected to different temperatures (*Note*: Dynamic modulus is calculated as the product of the density and square of pulse velocity).

significant reduction in the dynamic modulus is seen when the temperature is further increased to 90 °C. There is a 38% reduction at 65 °C and 75 °C whereas there is a 48% reduction at 90 °C.

Fig. 6 shows the change in length of specimens exposed to different temperatures. Data pertaining to thermal exposure for a period up to 300 days is presented. From the results, it can be inferred

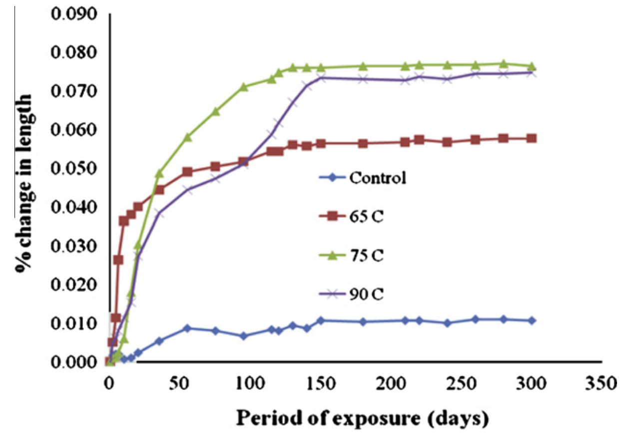

Fig. 6. Thermal expansion for concretes subjected to different temperatures.

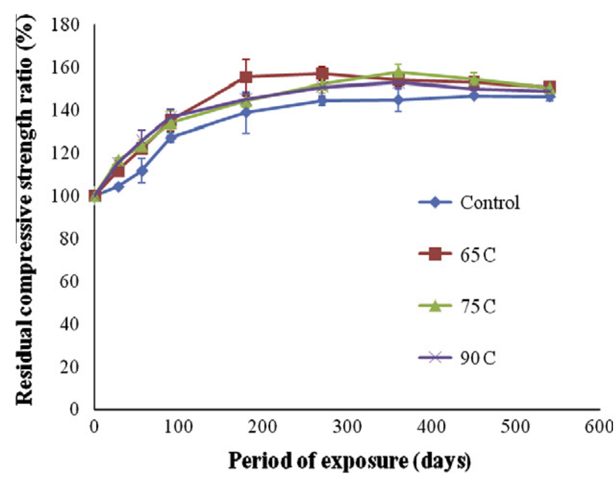

Fig. 7. Compressive strength development for concretes exposed to different temperatures.

that the change in length is higher for heated specimens and the thermal strains seem to be higher than the values calculated theoretically using the following equation:

$$\varepsilon = \alpha\,\Delta T \tag{1}$$

where, ε is the thermal strain, α is coefficient of thermal expansion (assumed here as 10×10^{-6}/°C), ΔT is the difference in temperature.

The expected thermal strain in concrete, calculated using Eq. (1), is around 350, 450 and 600 microstrains as the temperature increases from 30 °C to 65 °C, 75 °C and 90 °C, respectively. The expansion could be due to kinetic molecular movements in the cement paste at higher temperatures and swelling pressures caused by a decrease in capillary tension of water as the temperature rises [1,2]. Another possible explanation for the differences in thermal strain may be that the assumed coefficient of thermal expansion is not accurate for these materials. The expansion is found to cease after about 150 days of exposure.

4.2. Effects on mechanical properties of concrete

Compressive strength of the heated specimens was found to increase, as expected based on the literature [3,5,6], and at all ages, the strength of heated specimens was higher than the control. For 360 days exposure, there was a 46% increase at 75 °C and a 49% increase at 90 °C, compared to the 28 days strength of the

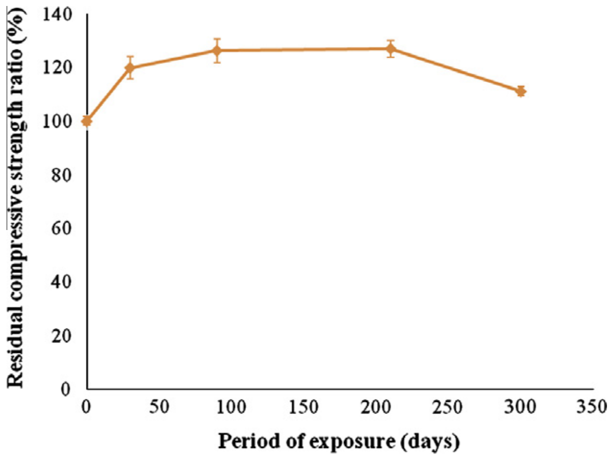

Fig. 8. Compressive strength for concrete subjected to thermal cycling.

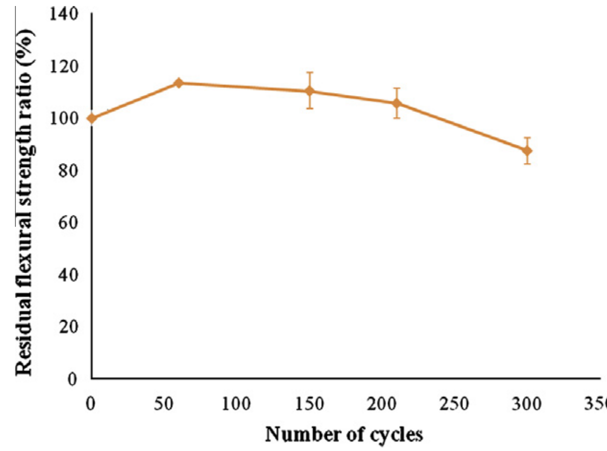

Fig. 10. Flexural strength for concrete after thermal cycling.

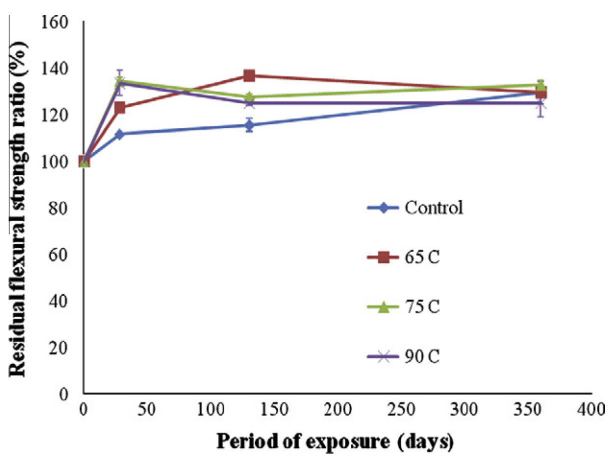

Fig. 9. Flexural strength for concretes exposed to different temperatures.

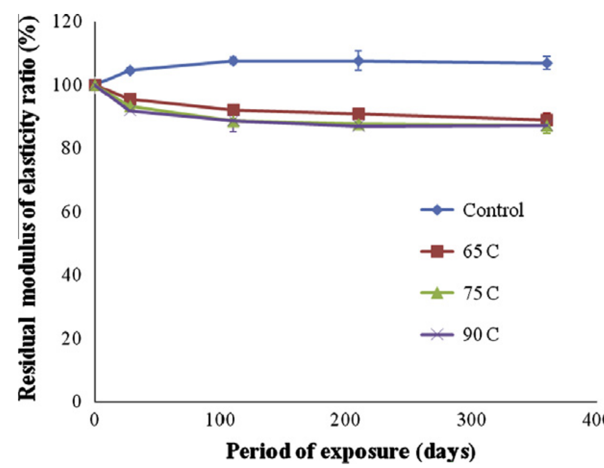

Fig. 11. Variation in modulus of elasticity due to heating at different temperatures.

concrete. The result of compressive strength tests up to 540 days exposure is presented in Fig. 7 (in the figure, residual compressive strength ratio refers to the strength of the exposed specimens as a percentage of the 28 days reference strength). Increase of strength in the heated specimens could be due to the confining effect of the partially saturated pores in cement paste [9]. In addition, moisture migration can lead to the hydration of any unhydrated cement and hence an increase in strength. Thermal cycling also did not cause a reduction in strength, in spite of the accelerated cycle used in the study (Fig. 8). The compressive strength of the thermal cycled specimens varied between 59 and 75 MPa, and was always higher than the control strength at 28 days.

Fig. 9 indicates that the flexural strength was found to increase by around 30% after 360 days for constant temperature storage. Results from thermal cycling, however, did indicate a marginal decrease in the flexural strength of concrete beyond 60 cycles of exposure. The decrease at 300 cycles, compared to the control value at 28 days, was 12.5% as seen in Fig. 10 (note that this is the difference between the mean values; however, the difference in error margins is less than 3%). This decrease in strength could be due to the microcracks formed at the interfacial transition zone during alternate heating and cooling.

Modulus of elasticity decreases as temperature increases and at all ages, it is lower than that of the unheated control concrete. As the results indicate in Fig. 11, the decrease was 11% at 65 °C and 13% at 75 °C and 90 °C (compared to 28 days control value) for 360 days of exposure – leading to a conclusion that the temperature of heating (up to 90 °C) does not affect the result. The moduli were seen to stabilise after an exposure period of about 120 days. This possibly indicates that the moisture migration may have ceased at this point (in agreement with the results in Fig. 3). Results for thermal cycling, in Fig. 12, indicate that after a decrease of about 14% after 90 cycles, the modulus of elasticity of the concrete remains constant, and only insignificant changes are noticed at later ages.

Also, it is to be noted that the elastic modulus of concrete exposed to 90 °C for a period of 360 days is 41.8 GPa, which is 13% less than that of the control specimen, but still 24.7% higher than the elastic modulus computed using IS 456 (2000) for M45 concrete (for M45 concrete, as per IS 456(2000), E value is 33.5 GPa). Thus, the modulus of elasticity upon heating stays well above the assumed design value during the time period of 1 year, indicating a satisfactory performance.

According to Mehta and Monteiro [9], regardless of mix proportions or curing age, concrete specimens that are tested in wet conditions show about 15% higher elastic modulus than the corresponding specimens tested in a dry condition. But the compressive strength of the specimen behaves in the opposite manner; that is, the strength is higher by about 15% when the specimens are tested in dry condition. This is because drying causes an increase in the van der Waals' forces of attraction in the hydration products, which increases the strength of the cement paste and hence

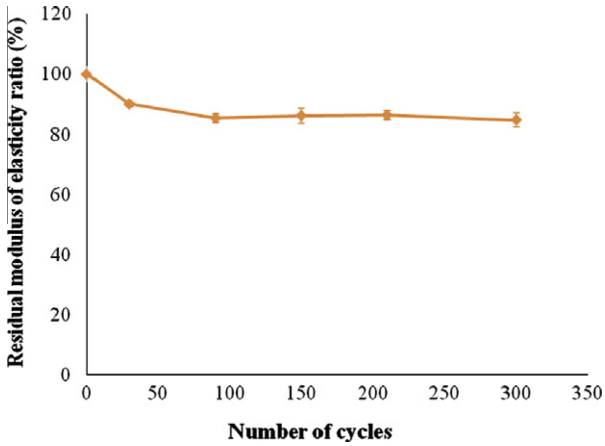

Fig. 12. Variation of modulus of elasticity of concrete exposed to thermal cycles.

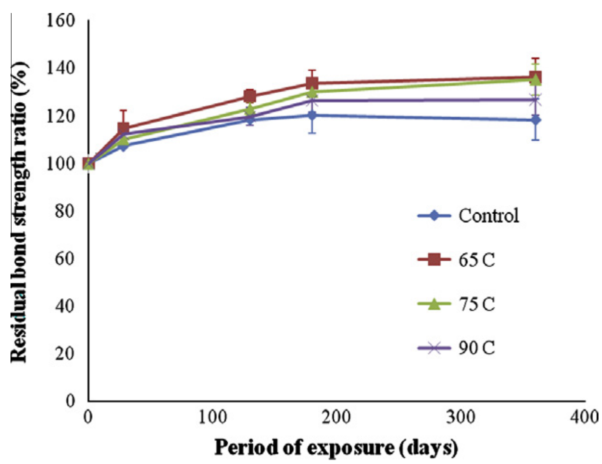

Fig. 13. Variation in bond stress of concrete exposed to different temperatures.

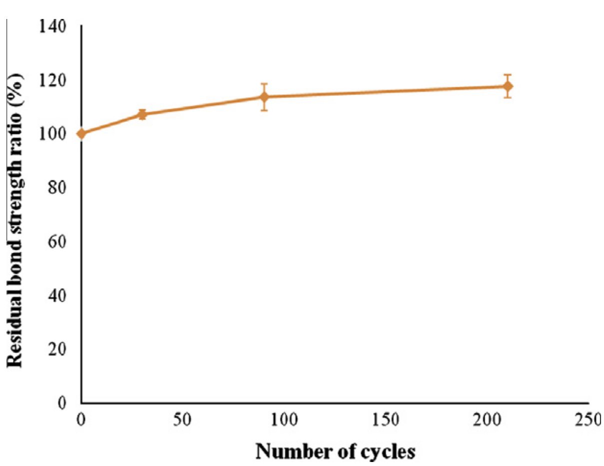

Fig. 14. Thermal cycling effects on the bond stress of concrete.

the compressive strength. Furthermore, drying causes a partial removal of water from the pores – thus, the capillary pressure associated with a partially saturated pore tends to produce a confinement effect, enhancing the concrete strength. On the other hand, drying produces the growth of microcracks in the interfacial transition zone, which causes a decrease in the elastic modulus.

Bond stress between the reinforcement bar and the concrete is found to increase, as shown in Figs. 13 and 14, respectively for constant temperature storage and thermal cycling. Compared to the unheated (reference) concrete at 28 days, the increase in bond stress is about 35% at 65 °C and 75 °C and 26% at 90 °C. Thermal cycling also causes a marginal increase of 17% at 210 cycles. In the investigations of Xiao and Konig [8], it is stated that the circumferential extrusion of concrete enhances the friction between concrete and rebar under high temperature, because the thermal expansion of concrete is less than that of rebar. This could explain the increase in bond between concrete and rebar at the moderately elevated temperatures investigated in this study.

5. Summary of results

This paper described experimental results for various engineering properties of normal aggregate concrete exposed to different elevated temperatures. Results from the study indicate the following:

(i) Compressive and flexural strengths are not adversely affected, and long-term exposure to high temperatures seems to produce an enhancement in the compressive and flexural strengths.
(ii) In contradiction to the increase in compressive strength, moduli of elasticity of the heated concrete are lowered compared to that of the control concrete. The reduction in modulus of elasticity does not seem to depend on the heating temperature, up to the highest level (90 °C) used in this study.
(iii) Bond stress is found to increase at all higher temperatures but the increase at 65 °C and 75 °C is more than that at 90 °C.
(iv) The study of physical properties indicates that the moisture migration effectively ceases beyond 50–80 days of exposure, resulting in a stabilisation of the concrete density as well as ultrasonic pulse velocity. The degree of deterioration, as measured by the dynamic modulus (from pulse velocity and density measurements), is marginally higher for the concrete exposed to 90 °C. However, there is no additional deterioration when temperature is changed from 65 °C to 75 °C.
(v) Results up to a period of 300 days indicate that there is a significant increase in thermal expansion when the temperature is 75 °C as compared to 65 °C.

The results from the measurements of mechanical properties conducted on concrete subjected to thermal cycling between 43 °C and 90 °C indicate the following:

(i) While compressive strength is not adversely affected for the concrete subjected to thermal cycling, the flexural strength seems to decrease in the long term. Bond strength is not affected even after 210 cycles.
(ii) Modulus of elasticity shows a reduction with thermal cycling. However, after 90 cycles, the modulus of elasticity does not change significantly with additional cycles.

6. Conclusions

The following conclusions can be drawn from the results obtained in this study:

(i) The change in exposure temperature from 65 °C to 75 °C does not affect the mechanical properties of concrete. Although marginal reductions in mechanical properties are noted at 90 °C, they are well within the design limits specified by AERB-CSE-1 and IS 456-2000.

(ii) Accelerated thermal cycling results in a greater degree of deterioration compared to exposure at constant heating temperatures. Hence thermal cycling becomes critical in determining the maximum permissible temperature in nuclear reactor vaults.

It must be noted that the results from this study are based on a 1 year period of investigation, which is relatively short term in regard to the actual life cycle of a nuclear vault concrete structure. Although a levelling-out tendency is seen in most properties, the response of concrete in the actual structure needs to be monitored using appropriate technologies. Further, mechanistic modelling of the response can also be attempted, with this data set providing a valuable validation for the model.

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References

[1] Bazant PZ, Kaplan FM. Concrete at high temperatures – Material properties and mathematical models. Harlow: Longman; 1996.
[2] Naus DJ. The effect of elevated temperature on concrete materials and structures—A literature review, NUREG/CR-6900. Washington: US Nuclear regulatory Commission; 2006.
[3] Naus DJ. A compilation of elevated temperature concrete material property data and information for use in assessments of nuclear power plant reinforced concrete structures, NUREG/CR-7031. Washington: US Nuclear regulatory Commission; 2010.
[4] Pihlajavaara SE. An analysis of the factors exerting effect on strength and other properties of concrete at elevated temperatures. ACI SP 1972;34:347–54.
[5] Nishizawa N, Okamura H. Strength and inelastic properties of concrete at elevated temperatures. ACI SP 1972;34:407–21.
[6] Harada T, Takeda J, Yamane S, Furumura F. Strength, elasticity and thermal properties of concrete subjected to elevated temperatures. ACI SP 1972;34:377–406.
[7] Zhang B, Bicanic N, Pearce CJ, Balabanic G. Residual fracture properties of normal and high strength concrete subjected to higher temperatures. Mag Concr Res 2000;52:399–409.
[8] Xiao J, Konig G. Study on concrete at high temperature in China—An overview. Fire Safety J 2004;39:89–103.
[9] Mehta PK, Monteiro PJM. Concrete-microstructure, properties, and materials. USA: McGraw-Hill; 1993.