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STRENGTH PROPERTIES OF CONCRETE AT ELEVATED TEMPERATURES

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INTRODUCTION

The strength properties of concrete at elevated temperatures are becoming a topic of increased interest in the design and analysis of advanced energy system facilities. These properties are currently being investigated by Burns and Roe, Inc., to provide a basis for the design and the evaluation of the Clinch River Breeder Reactor Plant (CRBRP) structures under accident temperatures associated with postulated large molten sodium coolant spills in lined cells.

This paper presents the results of a study performed to determine the elevated temperature compressive strength and elasticity properties of structural concrete and includes a summary of published test results, proposed design relationships, and the results of an experimental verification program. The relationships presented herein are based on interim test results reflecting ongoing research and development efforts, and are subject to change in the course of further development.

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DISCLAIMER

REVIEW OF PUBLISHED RESULTS

It has long been established that the compressive strength and the modulus of elasticity of structural concrete decrease with exposure to elevated temperatures. The magnitude and variation of the reduction in these properties with temperature is influenced by a multitude of factors resulting in a wide scatter of experimental results. Accordingly, an extensive literature study was carried out to determine the factors governing the elevated temperature strength and elasticity properties, to determine bounding exposure conditions for use in the development of a testing program, and to establish reliable and representative relationships. The published test results considered cover the range of temperatures from normal to 1600^{0}F and demonstrate that the effect of elevated temperature exposure is highly dependent upon the concrete mix and the testing methods and exposure conditions.

A review of the test methods used by various investigators has established that elevated temperature testing of concrete is separated into two general categories representing "cold" and "hot" testing. In cold testing the test specimens are heated gradually to a specified temperature, are allowed to remain or "heat soak" at that temperature for a period of time, then are allowed to cool to ambient and are then tested for compressive strength. In hot testing the specimens are heated gradually to the specified temperature, are allowed to heat soak and are tested while at that temperature. In both cases the test specimens are maintained in either an "open" environment, where water vapor can escape, or in a "closed" moisture migration system, where moisture is contained. Specimens are either "loaded" or "unloaded" during the heating and cooling phases.

A summary of published results on the residual compressive strength of concrete exposed to elevated temperatures is shown in Figure 1 for hot testing and in Figure 2 for cold testing. The effect of high temperature exposure on the modulus of elasticity is shown in Figure 3 for both hot and cold testing. A summary of the concrete properties and the testing conditions used by the various investigators is presented in Table 1. It should be noted that all the test results considered in this study are not presented in this paper but only selected and representative results. The following general observations are based on the literature study:

a. Specimens lose more strength if water (moisture) is not allowed to escape while heating than do specimens where the moisture is allowed to escape[7][11][17].

b. Specimens heated and then allowed to cool before testing lose more strength than those tested when hot (Figures 1, 2).

c. Concrete specimens loaded during heating lose less strength than unloaded specimens[1] [12].

d. The longer the duration of heating before testing, the larger the loss in strength. This loss of strength, however, stabilizes after a period of long isothermal exposure.

e. The decrease in the modulus of elasticity, due to elevated temperature exposure, is more pronounced than the decrease in compressive strength (Figures 1, 2, 3).

f. Mix proportions and type of aggregate influence the strength of heated concrete as follows:

lean mixes (low cements/aggregate ratio) lose less strength due to heating than richer mixes[12][17].

concrete made with limestone aggregate degrades less due to heating than concrete made with siliceous aggregate[8][6][17].

g. The water cement ratio has a limited effect on strength degradation of heated concrete[12].

h. Small test specimens usually incur greater strength losses than larger specimens.

i. Specimens subjected to several cycles of heating and cooling lose more strength than others without thermal cycling[5].

j. The strength of concrete before heating has little effect on the percentage of strength retained at elevated temperatures[1].

TABLE I

GENERAL DESCRIPTION OF TESTS AND CONDITIONS

SOURCE OF DATA	TEST METHOD Hot - (H) Cold - (C)	SYSTEM Open - (O) Closed - (C)	LOAD CONDITION Loaded - (L) Unloaded - (UL)	AGGREGATE	MIX* PROPORTIONS	WATER CEMENT RATIO	LENGTH OF HEAT EXPOSURE
Abrams (1)	C H	O O	UL UL	Carbonate "	1:3.6:4.6 "	0.55 "	3-4 hrs. "
Campbell, Lower and Roper (5)	C	O	UL	Dolorite	1:1.8:1.3	0.44	6-8 hrs.
Hannant (7)	C	C	L	Limestone	NA	NA	2-4 hrs.
Harada et al (8) LB UB	H H	O O	UL UL	Gravel Gravel	1:2:2 1:3:3	0.45 0.70	1-2 hrs. 1-2 hrs.
Lankard et al (11)	H	C	UL	Gravel	1:1.9:3.4	0.42	4-6 hrs.
Malhotra (12)	H C	O O	UL UL	Flint "	1:4.5 "	0.45 "	2-3 hrs. "
Marechal (13)	H	O	L	Siliceous limestone	NA	NA	NA
Nasser and Lohtia (14)	C	C	UL	Dolomite	NA	0.6	14 days
Ohgishi et al (15)	C H	O O	UL UL	Gravel "	1:4:6 "	0.45 "	< 1 hr. "
Miller and Faulkner (6)	C	O	UL	NA	1:2:4	N	4 hrs.
Roux (17)	H	O	UL	NA	NA	0.58	NA
Wierig (16)	C	O	UL	NA	NA	NA	NA
Zoldners (18)	C	O	UL	Limestone	1:3.2:3.5	0.63	1-2 hrs.

NA = Not Available

*Cement: Fine Aggregate: Coarse Aggregate

BOUNDING CONDITIONS FOR CONFIRMATORY TESTING

From the literature study it was concluded that the lower bound response of concrete at elevated temperatures must be assessed at two sets of test conditions. The definitions of these two lower bound test conditions are:

a. Open-Hot Testing:

Under open-hot testing the concrete specimens are heated in an open moisture migration environment which allows free loss of moisture. The specimens are tested for compressive strength while hot and after a period of temperature stabilization. Specimens are heated while unloaded.

Testing under these conditions simulates the response of a concrete element during a thermal accident where the element is either vented or has free atmospheric communication. (Figure 4)

b. Closed-Cold Testing:

Under closed-cold testing the concrete specimens are heated in a closed moisture migration environment preventing the release of moisture from the concrete specimens. They are heated while unloaded and allowed to stabilize at a test temperature before cooling down slowly to ambient conditions. The specimens are tested for compressive strength following the cool down (cold).

Testing under these conditions simulates the response of a concrete element after a thermal accident. The atmospheric condition is representative of a concrete element located within an unvented region or within a massive concrete structure.

These two test conditions conservatively bound the worst case response of a structural concrete element exposed to a prolonged elevated temperature.

DESIGN RELATIONSHIPS

In order to develop design relationships the upper and lower bound response curves from the literature study were used to construct the residual compressive strength curves corresponding to concrete tested while at elevated temperature (Figure 1) and to concrete tested after cool down (Figure 2). Of the two conditions the larger reduction in strength occurs for the cold conditions and may conservatively be used as an overall lower bound. In addition, upper and lower bound curves were established from the literature study data for the residual modulus of elasticity (Figure 3). Perhaps due to the lack of sufficient data on this property, different relationships for hot versus cold testing conditions were not revealed by the literature. However, the verification work described hereafter seems to support that testing conditions do not significantly affect the modulus of elasticity.

In the evaluation of concrete structures subject to thermal gradients both the compressive strength (f_c') and the stiffness, a function of the modulus of elasticity (E), are important parameters. The compressive strength influences the load carrying capacity, while the stiffness relates to deformations and the forces developed by the various restraints. At elevated temperatures a direct result of the decrease in strength and stiffness is a reduction in the load carrying capacity and the induced thermal forces respectively. Hence, a lower bound curve for compressive strength is conservative for capacity while an upper bound curve for E, a measure of stiffness, is conservative with respect to thermal forces. Design relationships, however, based on a lower bound curve of one parameter and an upper bound curve for the other will lead to undue conservatism since the test results indicate correspondence between the upper and lower bound curves. More rationally the response to thermal gradients may be bracketed by comparing the response between the upper bound strength and elasticity and the lower bound strength and elasticity design relationships.

The resultant relationships developed to depict the upper and lower bound response of commonly used types of structural concrete exposed to elevated temperatures for compressive strength and modulus of elasticity are shown in Figures 4 through 7 for the open-hot and closed-cold test conditions. These relationships are presented with the results of a verification testing program which is summarized in the following section.

VERIFICATION TESTING PROGRAM

The information obtained from the study of the published results was used as a basis for implementing a confirmatory verification testing program which was carried out at Oak Ridge National Laboratory (ORNL) and published in Reference 4. The objective of the program was to test mature concrete under prototypic exposure conditions to verify the bounding relationships established via the literature study. To obtain a lower bound reduction of concrete strength the cylinders were tested in a semi-closed moisture migration environment after gradual cool down ("closed-cold"). To establish a relationship for hot testing the cylinders were tested in an open moisture migration environment while at the elevated temperature ("open-hot"). In both cases the test cylinders were exposed to high temperatures while unloaded.

The testing was performed on 8 to 19 month old concrete cylinders (6" diameter x 12") of a limestone aggregate mix similar to that proposed for use in the CRBRP structures. All of the concrete cylinders tested were heated to their test temperatures at a rate of 30^{o}F/hr. and were maintained at the test temperature for 14 days. Details of the testing equipment, procedures and the specimens are given in Reference 4.

The relationships for residual compressive strength obtained from this testing program are shown in Figures 4 and 5 for open-hot and closed-cold test conditions respectively. On the same figures are shown the relationships established from the literature which are confirmed by the verification test results. Relationships for the residual modulus of elasticity under open-hot and closed-cold conditions are shown in Figures 6 and 7. These results fall within the established bounds and are closer to the lower bound design relationship.

The residual compressive strength was established by comparing the actual compressive test results with the strength of the cylinders immediately before heat up. The strength of companion cylinders was used in the determination of the test cylinder strength before heating. This procedure eliminated the variable of strength gain with age from the design relationship.

The strength gain with age, for the particular concrete mix used in this testing is shown in Figures 4 and 5. The upper curves show the ratio of values for approximately one year old cylinders heated to the test temperature over companion unheated specimens tested at 28 days. These curves indicate that cylinders which have gained strength with age degrade to values below the 28 day strength only after significant heating. Although similar gains occur in the modulus of elasticity (Figure 7), the age effect often results in conservatism which may be an important factor to consider in the evaluation of structures particularly for events that are of extremely unlikely occurrence.

STRESS-STRAIN RELATIONSHIPS

The evaluation of structures under conditions resulting in low mechanical strains involves elastic analysis procedures for which it is sufficient to know the modulus of elasticity and the strength of the material. Whenever large strains are involved, however, as is usually the case with elevated temperatures, the evaluation of structures requires elastic-plastic analysis procedures and use of stress deformation relationships. For this reason the development of stress-strain relationships for concrete at elevated temperatures is essential.

The generally accepted stress-strain diagram for concrete begins with a nearly linear portion then as cracking takes place it deviates from linearity at an increasing rate until it reaches the maximum stress. Beyond this point, as significant cracking takes place, the curve descends until failure occurs. A number of mathematical equations have been proposed by various authors to express the relationship between stress and strain in concrete. In general, these expressions are in good agreement with the ascending part of the curve but differ significantly beyond the point of maximum stress. The stress-strain relationship proposed by Kent and Park(10) was selected in this study to define the behavior of concrete at normal temperature and to serve as a basis for establishing relationships for concrete at elevated temperatures. This relationship is given by the following expressions:

$$f_c = f'_c \left[2\left(\frac{\varepsilon_c}{\varepsilon_o}\right) - \left(\frac{\varepsilon_c}{\varepsilon_o}\right)^2 \right] \qquad 0 < \varepsilon \leqslant \varepsilon_o \qquad (1a)$$

$$f_c = f'_c \left[1 - Z\,(\varepsilon_c - \varepsilon_o) \right] \qquad \varepsilon > \varepsilon_o,\ f_c \geqslant 0.2 f'_c \qquad (1b)$$

$$f_c = 0.2\, f'_c \qquad \varepsilon > \varepsilon_o,\ f_c < 0.2 f'_c \qquad (1c)$$

where:

f'_c is the maximum stress;

ε_o is the strain corresponding to maximum stress and is equal to 0.002 in/in;

$Z = 0.5/(\varepsilon_{50h} + \varepsilon_{50\mu} - \varepsilon_o)$ is the slope of the descending branch of the curve;

$\varepsilon_{50\mu} = (3 + 0.002 f'_c)/(f'_c - 1000)$ is the strain corresponding to $0.5 f'_c$ on the descending branch of the σ-ε curve for unconfined concrete;

ε_{50h} is the difference in strain between confined and unconfined concrete at $0.5 f'_c$ on the descending branch of the σ-ε curve. For unconfined concrete considered here ε_{50h} equals zero.

The expression for the ascending part of the curve is essentially the same as that proposed by Hognestad[9]. Beyond the maximum stress the curve, for unconfined concrete, descends at a faster rate than the curves proposed by other authors and has been found to agree well with experimental results.

The stress-strain relationship for concrete at elevated temperatures is similar to that at normal temperature except that the maximum stress is attained at much higher strains in the case of elevated temperatures. In Reference (2), it is shown that the relationship at elevated temperatures may be derived from that at normal temperatures if the variation of maximum stress and the corresponding strain with temperature is known.

The variation of the maximum compressive stress with temperature is defined by the upper and lower bound design relationships shown in Figures 1 and 2. The variation of ε_o, the strain corresponding to maximum stress, with temperature has been derived using the results obtained by Furamura and reported in Reference (2) together with results from the testing program at ORNL. The proposed relationship is shown in Figure 8 where the ratio of ε_o at elevated temperatures to ε_o at normal temperature is plotted against temperature. Using these data, stress-strain curves at different temperatures were developed corresponding to hot and cold testing and upper and lower bounds for strength and elasticity.

Temperature dependent σ-ε curves corresponding to lower bound relationships and f'_c = 4000 psi before heating, are shown in Figures 9 for hot testing and in Figure 10 for cold testing conditions. These curves were obtained from Equation (1) with values of maximum stress based on the design relationships in Figures 1 and 2 and corresponding strains, ε_o, calculated from Figure 8 with ε_o = 0.002 in/in at normal temperature. The values of the modulus of elasticity corresponding to these curves agree well with the lower bound relationships although somewhat higher and hence more conservative.

A set of stress-strain curves corresponding to the upper bound strength and elasticity relationships for cold or hot testing and f'_c = 4000 psi before exposure to high temperatures, are shown in Figure 11. These curves were obtained in a similar manner except that values of ε_o in this case were calculated from the derivative of Equation (1a) instead of Figure 8 which would have resulted in unconservative values for E.

The stress-strain curves derived from the lower bound design relationships for cold testing are significant in post-accident evaluations of structures and of course they represent a lower bound under any conditions of temperature exposure. The curves corresponding to hot conditions are more realistic for structures under thermal gradients and provide sufficient conservatism.

The stress-strain relationships in Figures 9, 10 and 11 are presented with no limit on strains. Beyond the point of maximum stress, however, the cracking becomes significant and failure occurs at some lower stress level. The values of ultimate or failure strains vary widely depending on the type of concrete mix, the testing methods, the degree of confinement and other factors. The ACI 318-77 Specification[3] limits the maximum usable strain at normal temperature to 0.003 in/in, a lower bound value for unconfined concrete. For concrete exposed to elevated temperatures the strains corresponding to maximum stress are substantially higher than those at normal temperatures (Figure 8) and failure strains are expected to be also higher. A modest increase of the ACI limit to 0.004 in/in for temperatures of 500°F and above is deemed both realistic and safe in view of the above considerations.

SUMMARY AND CONCLUSIONS

A study has been presented concerning the strength properties of concrete at elevated temperatures and includes a review of published test results, the development of design relationships, and the results of an experimental verification program. The review of the published results provided information for the development of relationships for compressive strength and modulus of elasticity, and established the test conditions for a lower bound thermal response. The relationships developed correspond to hot and cold test conditions and show that exposure to elevated temperature results in significant losses in compressive strength and elasticity. The relationships were confirmed by the results of a verification testing program carried out at the ORNL. Finally, the strength and elasticity relationships provided a basis for the development of stress-strain curves at elevated temperatures, which are essential for elastic plastic procedures and capacity calculations.

ACKNOWLEDGMENT

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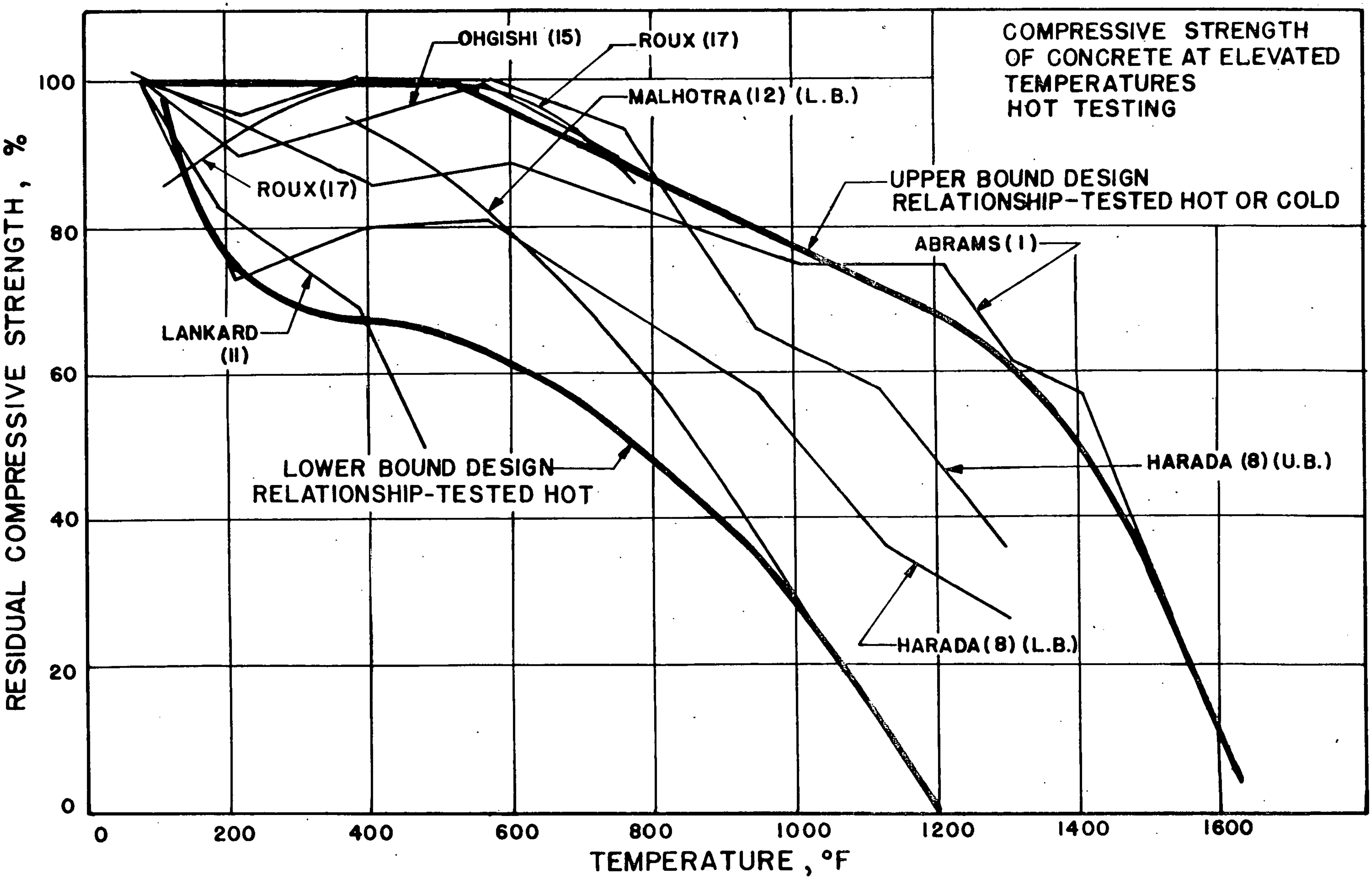

FIG. 1 - EFFECT OF TEMPERATURE EXPOSURE ON THE COMPRESSIVE STRENGTH OF CONCRETE - HOT TESTING

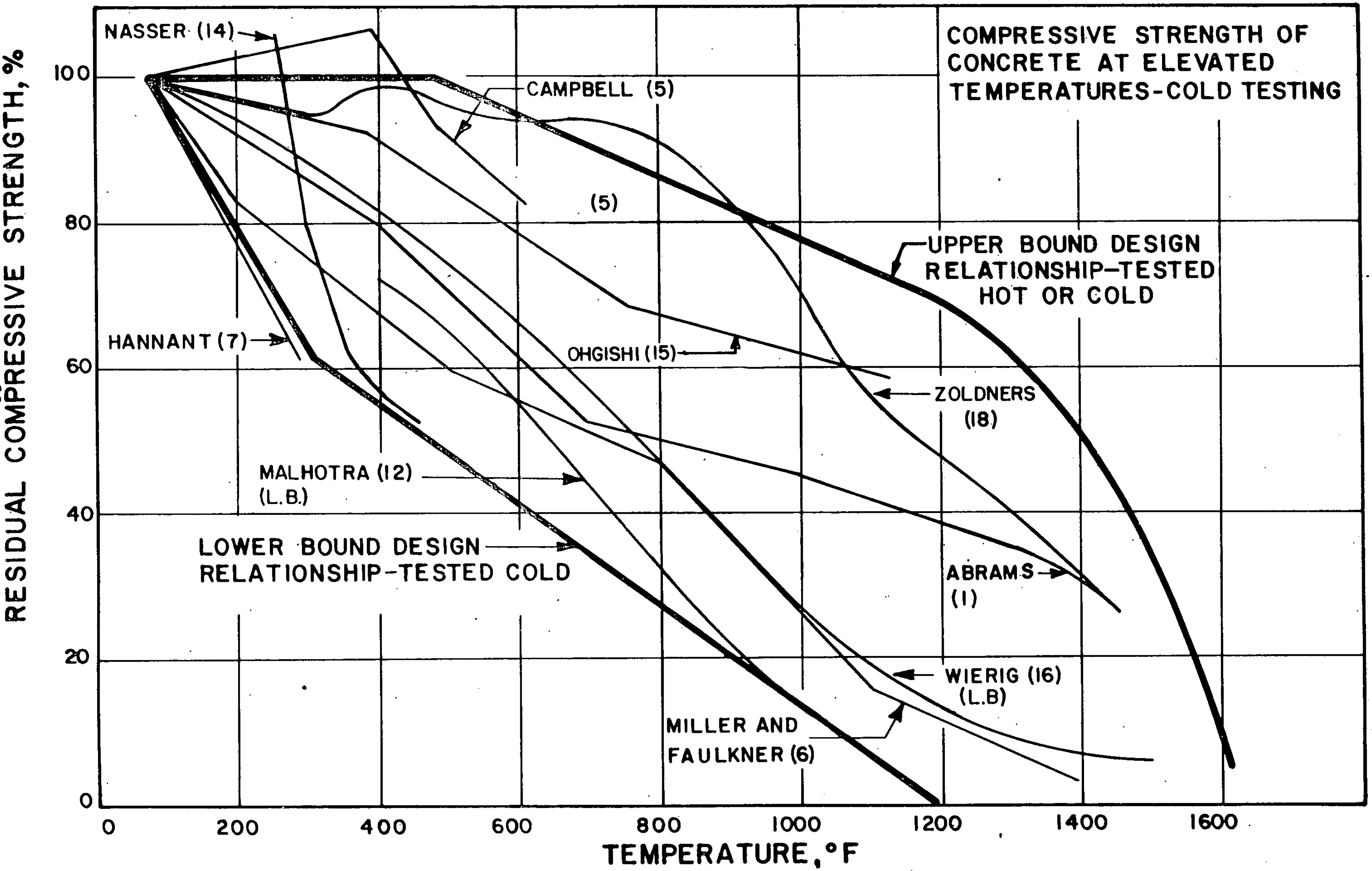

FIG. 2 - EFFECT OF TEMPERATURE EXPOSURE ON THE COMPRESSIVE STRENGTH OF CONCRETE - COLD TESTING

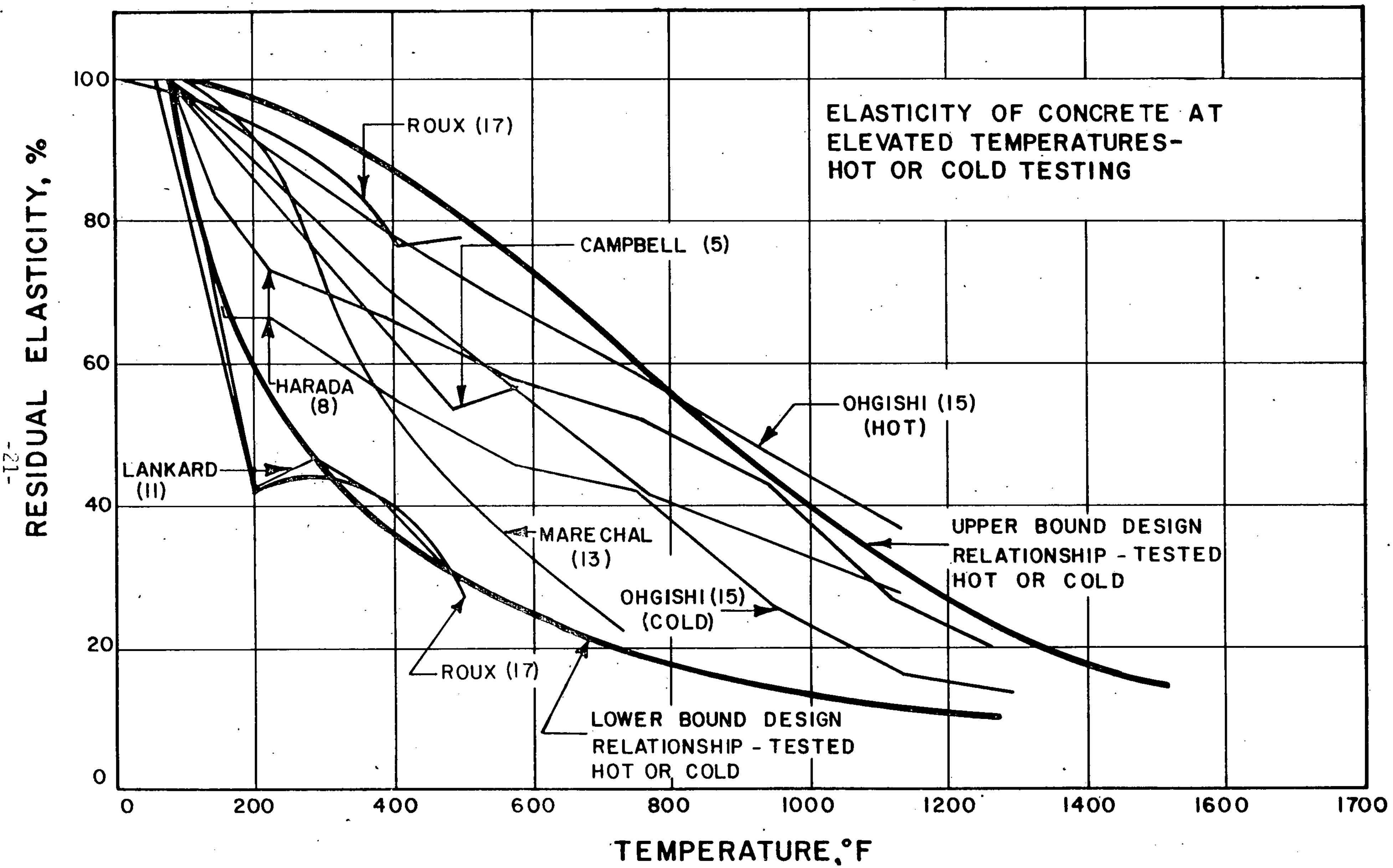

FIG. 3 - EFFECT OF TEMPERATURE EXPOSURE ON THE MODULUS OF ELASTICITY OF CONCRETE - HOT OR COLD TESTING

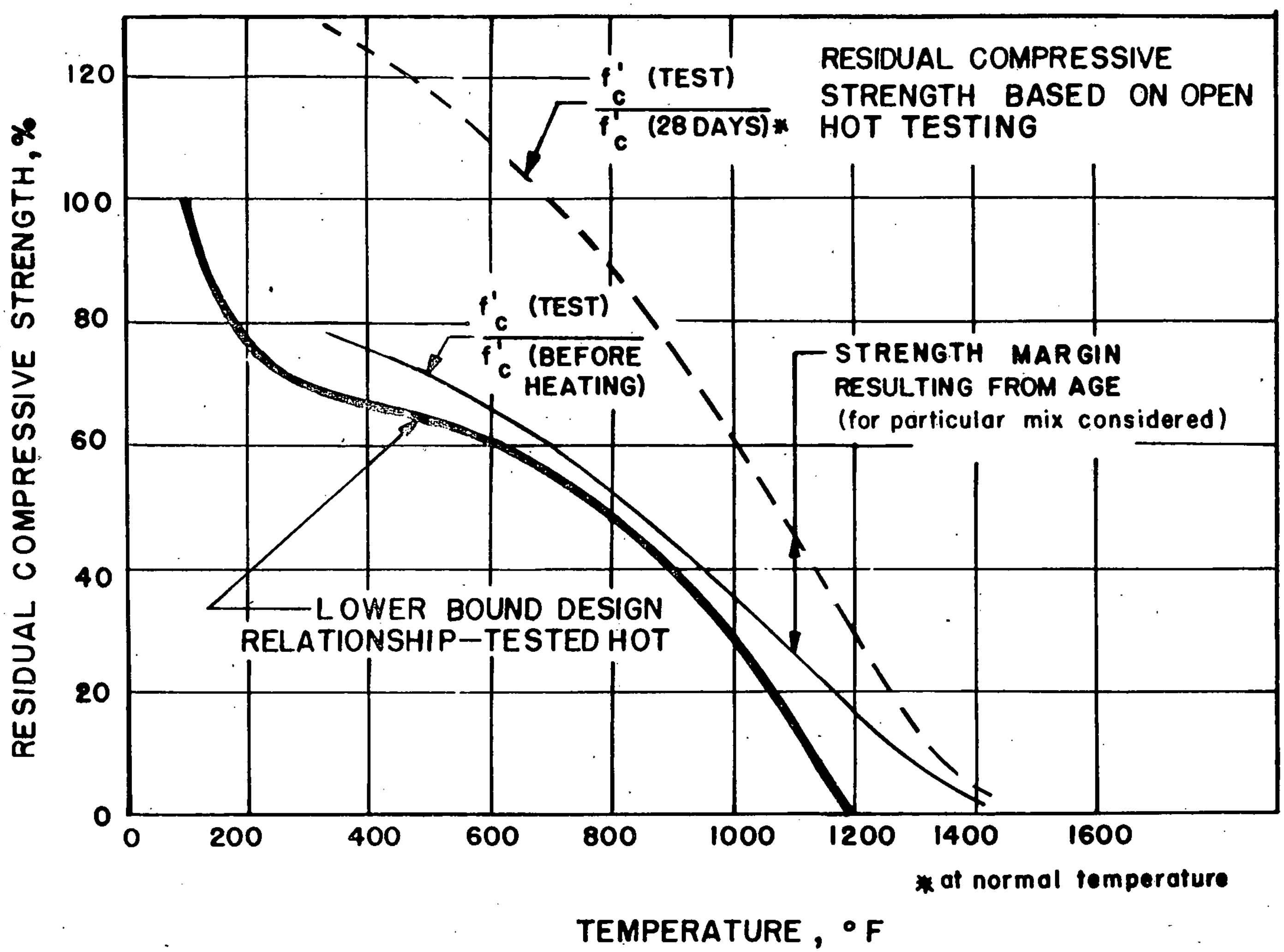

FIG. 4 - RESIDUAL COMPRESSIVE STRENGTH OF CONCRETE BASED ON OPEN-HOT TESTING

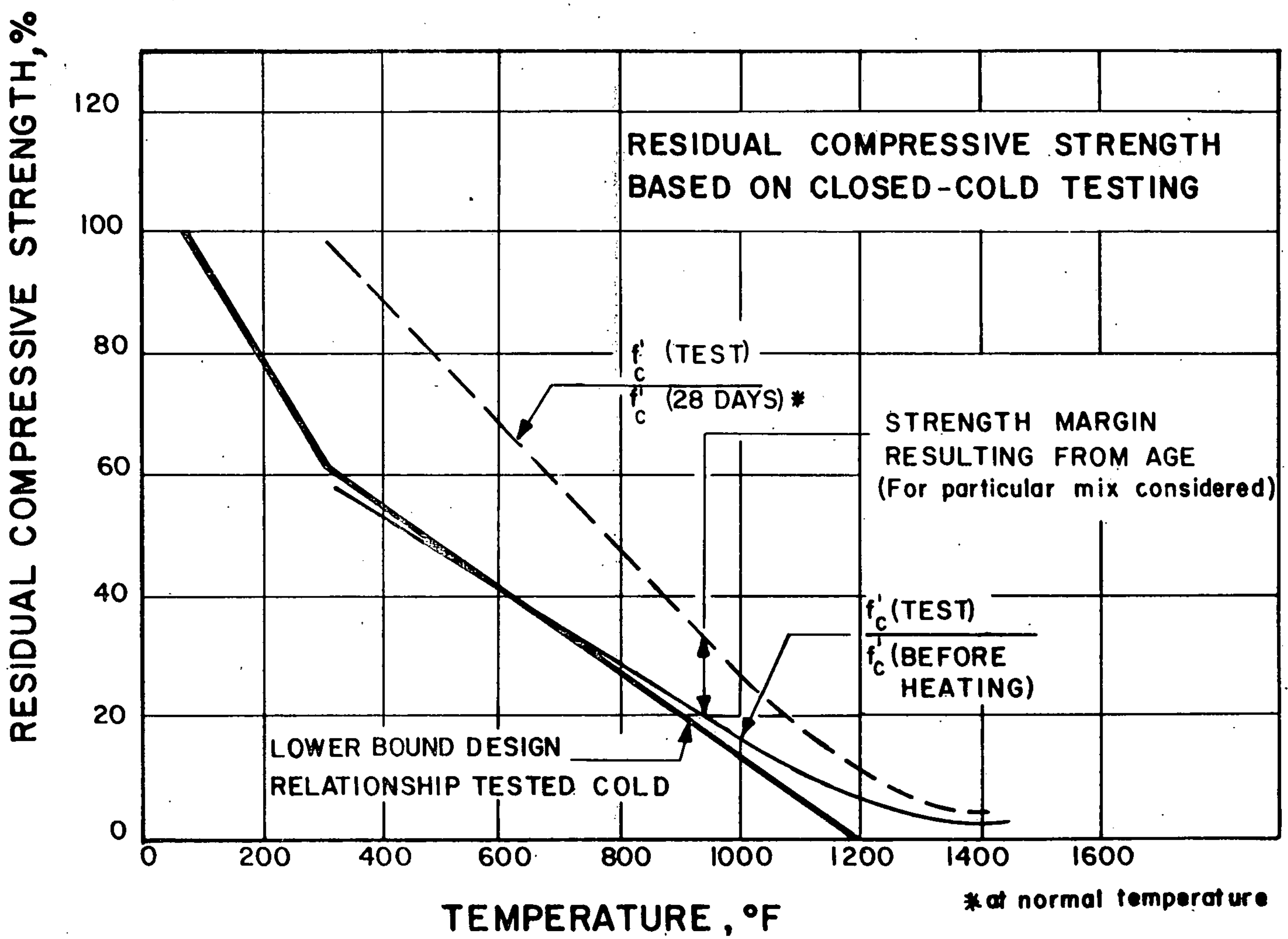

FIG. 5 - RESIDUAL COMPRESSIVE STRENGTH OF CONCRETE BASED ON CLOSED-COLD TESTING

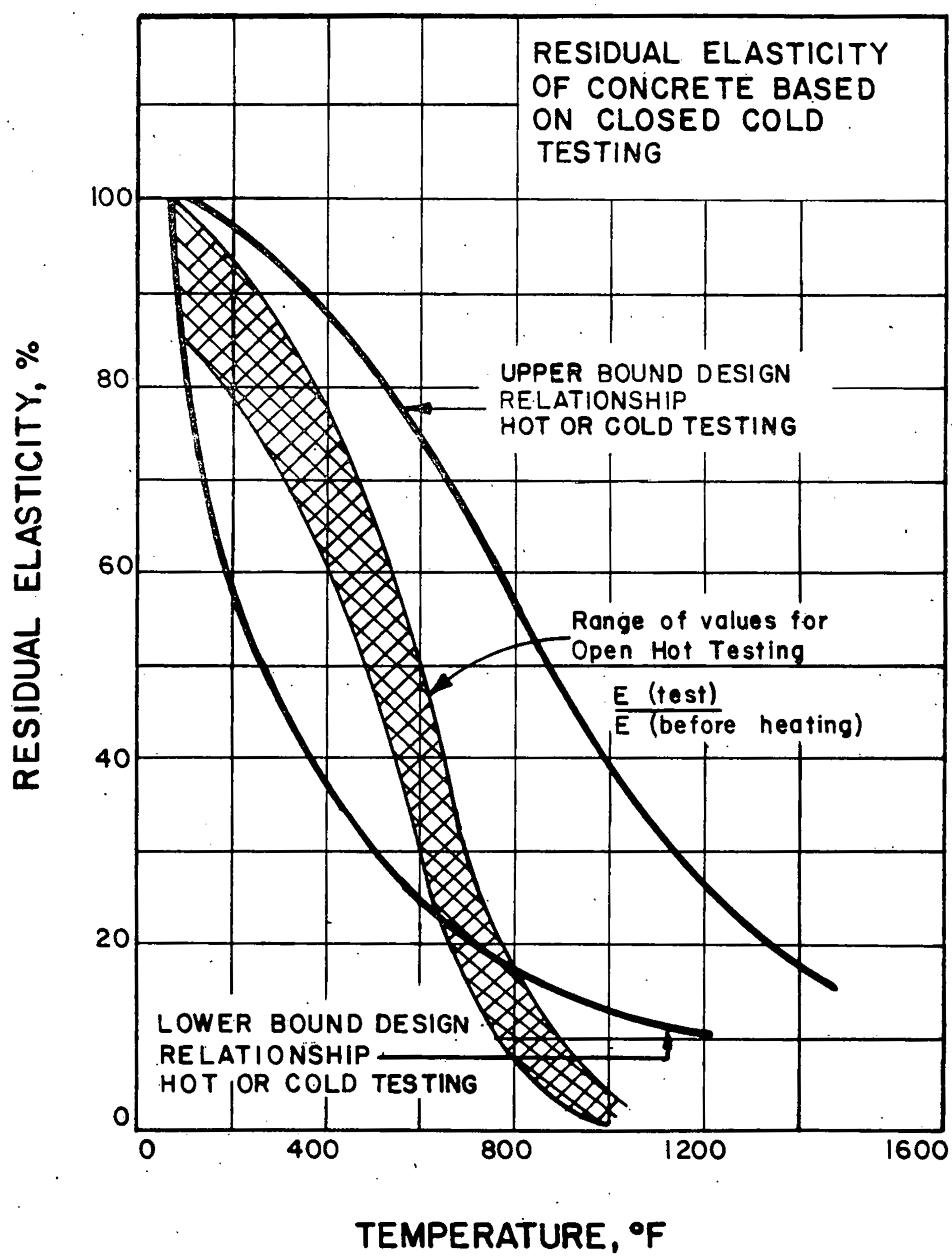

FIG. 6 - RESIDUAL MODULUS OF ELASTICITY OF CONCRETE BASED ON OPEN-HOT TESTING

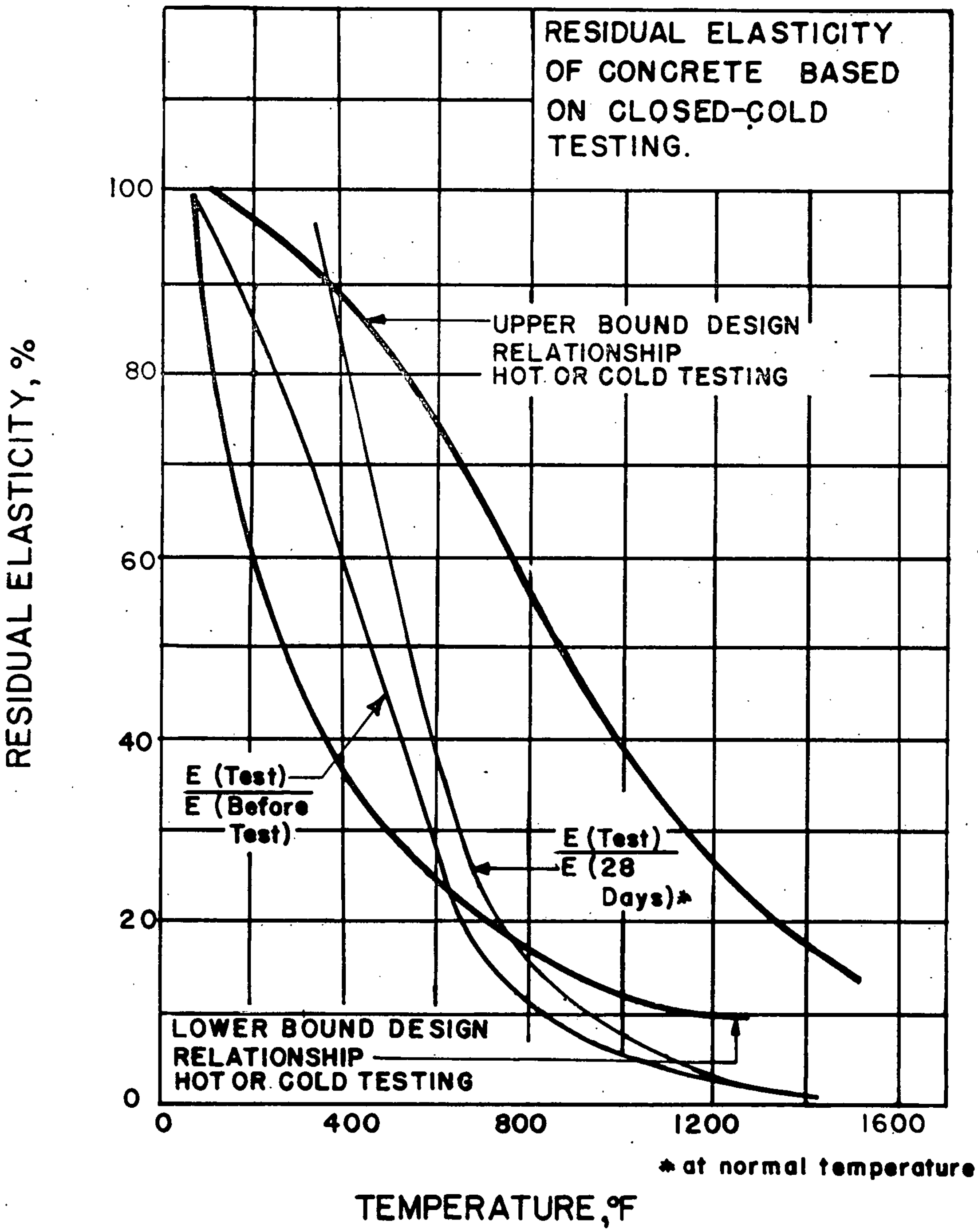

FIG. 7 - RESIDUAL MODULUS OF ELASTICITY OF CONCRETE BASED ON CLOSED-COLD TESTING

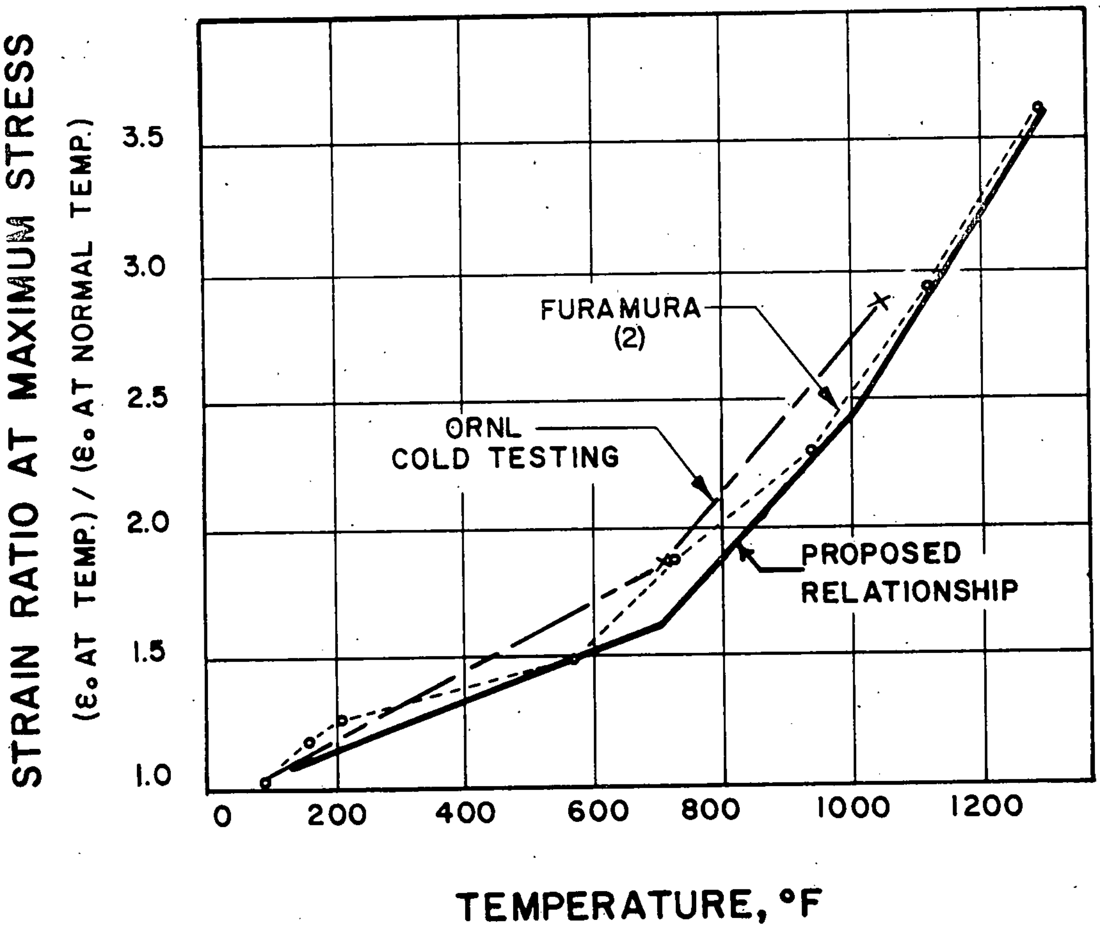

FIG. 8 - EFFECT OF TEMPERATURE ON THE STRAIN AT MAXIMUM STRESS

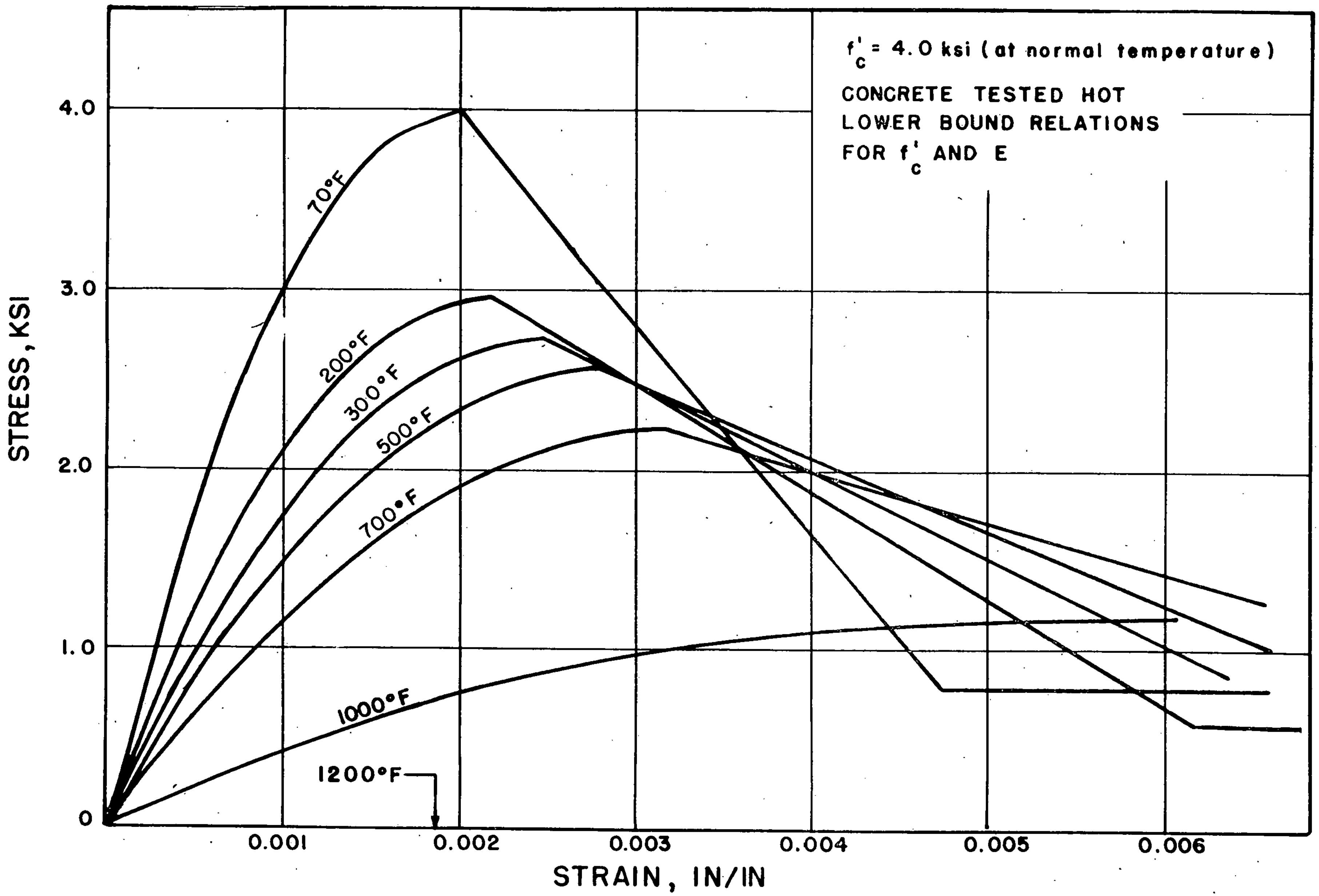

FIG. 9 - STRESS-STRAIN RELATIONSHIP - CONCRETE TESTED HOT

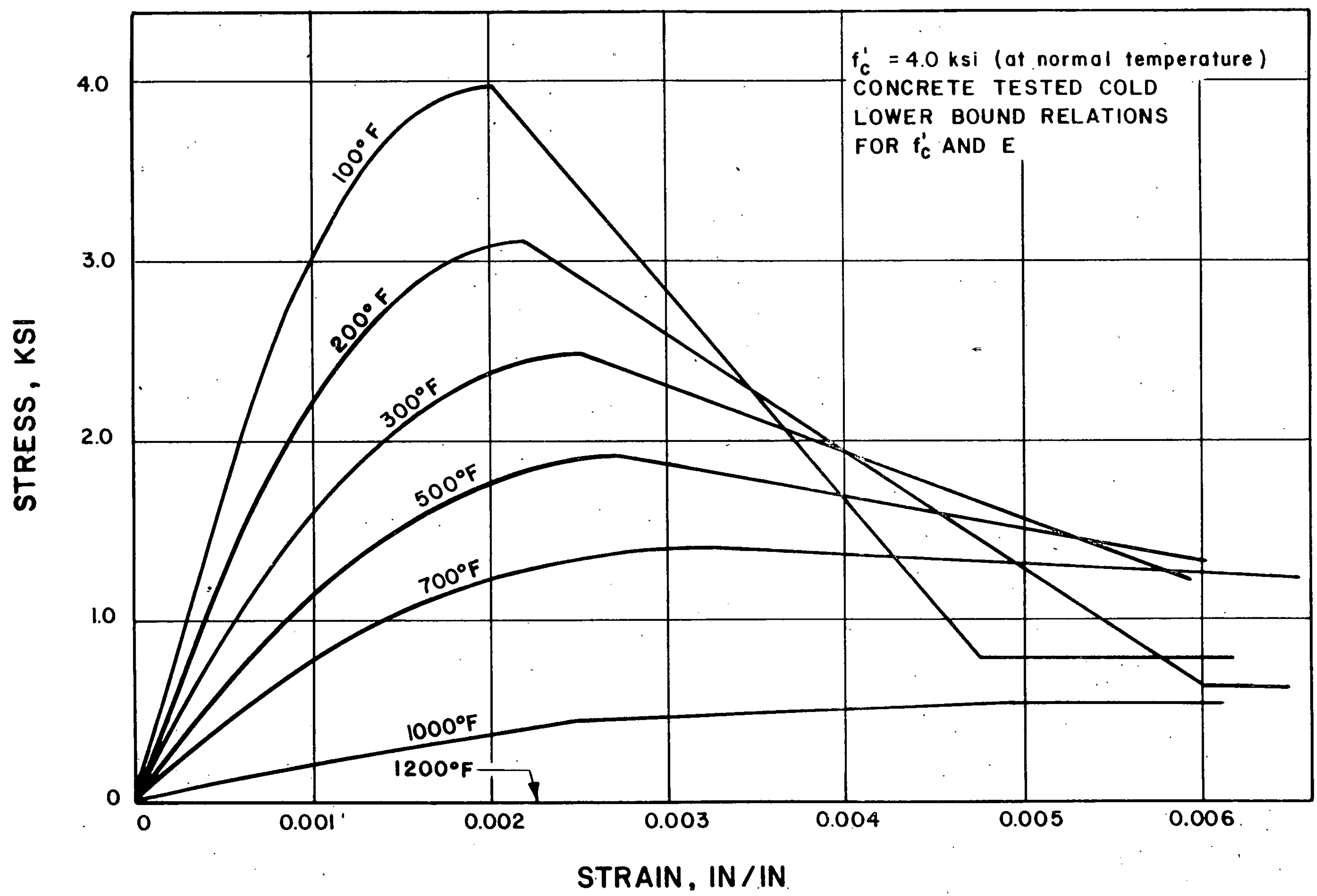

FIG. 10 - STRESS-STRAIN RELATIONSHIP - CONCRETE TESTED AFTER COOLING DOWN

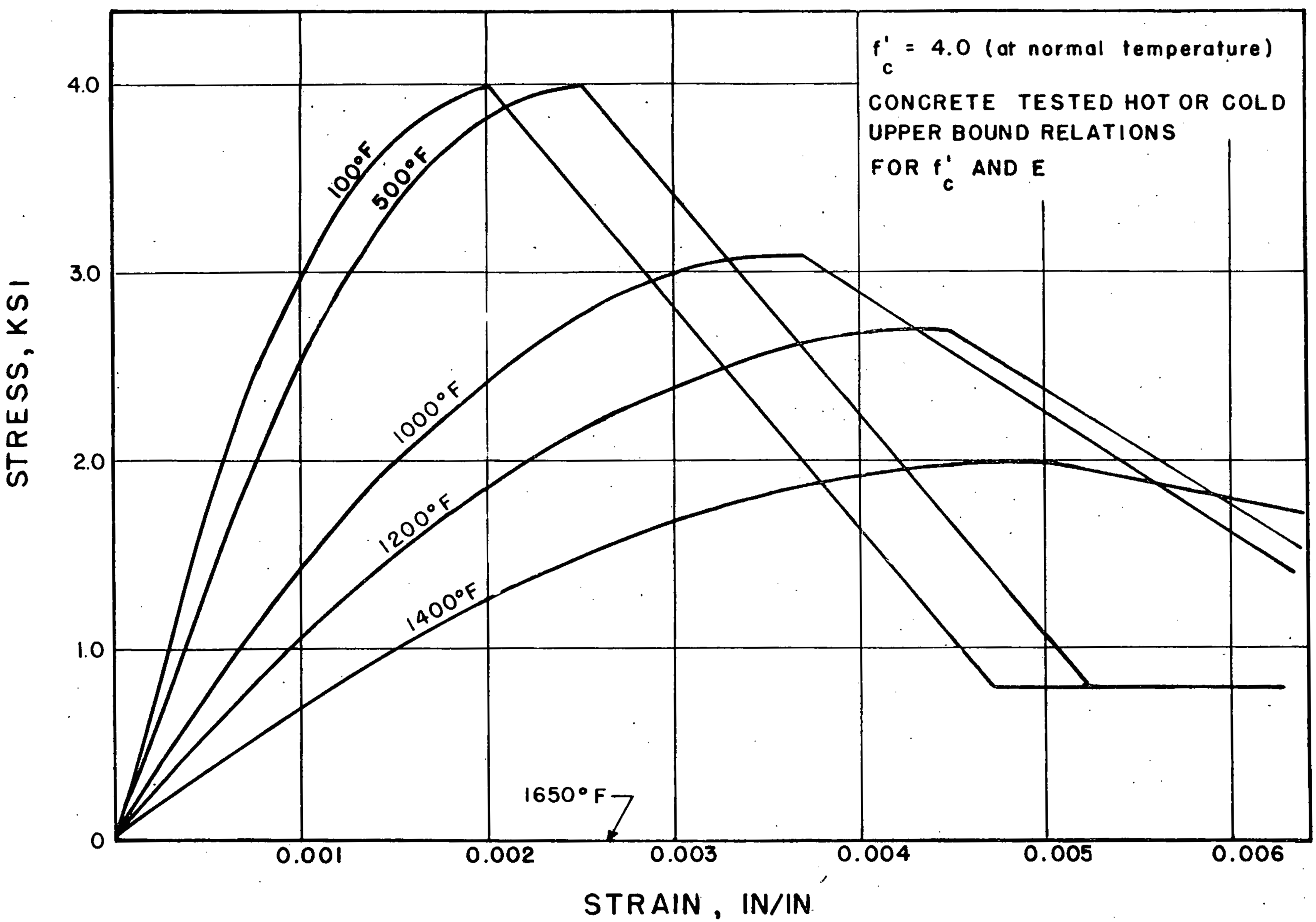

FIG. 11 - STRESS-STRAIN RELATIONSHIP -- CONCRETE TESTED HOT OR COLD

STRENGTH PROPERTIES OF CONCRETE AT ELEVATED TEMPERATURES

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KEY WORDS: Compressive strength; concrete; elevated temperatures; Modulus of Elasticity; Stress-Strain relationships; concrete testing.

ABSTRACT: A study is presented concerning the compressive strength, modulus of elasticity, and stress-strain relationships of concrete at elevated temperatures. A review of published results provides information for the development of upper and lower bound relationships for compressive strength and the modulus of elasticity and establishes exposure conditions for a lower bound thermal response. The relationships developed from the literature review are confirmed by the results of a verification test program. The strength and elasticity relationships provide a basis for the development of design stress-strain curves for concrete exposed to elevated temperatures.