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Concrete At Elevated Temperatures

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ABSTRACT

This paper modelled the experimental results of Ehm (1986) and Thelandersson (1987) on transient thermal creep of concrete specimens, under sustained load, at elevated temperatures and investigated the relevance of transient thermal creep on the behaviour of concrete at elevated temperatures. Numerical investigations were carried out on steady state and transient state models using the 'Finite Element Analysis Programme' (FEAP). The investigations included observing the effect of degraded coefficient of thermal expansion and modulus of elasticity of concrete with and without the inclusion of the effect of transient thermal creep (assumed equivalent to the effect of thermo mechanical strain) on the behaviour of concrete, observing the relevance of the transient thermal creep on the behaviour of concrete and observing the effect of sustained compressive stress on the temperature dependent compressive strength of concrete. The study showed that the model predictions fit the experimental results and confirmed i) the absence of transient thermal creep in steady state specimens, ii) that the coefficient of thermal expansion and modulus of elasticity of concrete are degraded at elevated temperatures, iii) that the coefficients of thermo mechanical strain and free thermal expansion changed respectively at 469°C and 619°C and iv) that the critical temperature of concrete decreases with increase in the magnitude of the sustained compressive stress.

Keywords: Concrete; elevated temperature; load-induced thermal strain; thermo mechanical strain; transient thermal creep.

1. Introduction

For a concrete specimen subjected to transient temperature and load, the total uniaxial strain rate $\acute{\varepsilon}_{tot}(T,\sigma)$ obtained under the first heating comprises of the mechanical (or elastic) strain rate $\acute{\varepsilon}^{\sigma}(T,\sigma)$, the free thermal strain rate $\acute{\varepsilon}_{th}(T)$, the creep strain rate $\acute{\varepsilon}_{c}(T,\sigma)$ and the thermo mechanical strain rate $\acute{\varepsilon}^{\sigma}_{th}(T,\sigma)$ [1]. The last two terms are combined to give the load-induced thermal strain rate abbreviated lits by Khoury et al, [2]. The shrinkage strain rate, assumed included in the thermal strain rate for unsealed test specimens, is independent of loading [1].

Creep and thermo mechanical strains cannot be separated experimentally. Their usage is mainly theoretical and has little practical implications for short duration heating [3]. Hence, the subdivision is simply to show that the two components have different characteristics. This is because while the creep component takes place under both heating and cooling and therefore shows creep recovery, thermo mechanical strain is only experienced during the first heating and not during subsequent cooling or heating cycles [4]. Hence, the load-induced thermal strain represents an irrecoverable strain component that is crucial to the response of a concrete member at high temperatures because it could lead to severe tensile stresses during cooling [5].

The load-induced thermal strain is determined experimentally by measuring the total strain during the first time heating of a concrete specimen under sustained loading and subtracting the free thermal strain and the initial elastic strain obtained for an unstressed specimen from it. Other approaches suggested for determining the load-induced thermal strain are the ones by Schneider [6, 7] where thermo mechanical strain is said to be a non-linear function of stress, Khoury et al. [4, 2], Thelandersson [7], Terro [8] who applied a fourth order polynomial to fit the master curve suggested by Khoury et al. [2] and Nielson et al. [1]. Since the creep strain is minor when compared with the thermo mechanical strain, the thermo mechanical strain is assumed proportional to the thermal strain [7]. While de Borst and Peeters [9] and Khennane and Baker [10] adopted this assumption, Nielsen et al [1] adopted a more general formulation in which the upper and the lower bounds of the parabolic model were based respectively on the results of Schneider [3] and Khoury et al. [2] modelled by Terro [8].

The ratio between the creep strain and thermo mechanical strain (about 15-20% at a rate of heating of 0.05°C/min) decreased as the rate of heating increases and at the practical experimental values of the rate of heating (typically above 1°C/min) it becomes reasonable to neglect the creep component under test conditions [1]. Using the steady-state creep strain formula proposed by Schneider [6], Nielson et al. [1] showed that the creep strain is insignificant when compared with the thermo mechanical strain at the rates of heating above 1^{o}C/min. Since the creep strain becomes insignificant as the rate of heating increases, the load-induced thermal strain could be assumed equivalent to the thermo mechanical strain at the practical rates of heating. Nielsen et al. [1] also reported that the elastic strain is insignificant when compared with the thermo mechanical strain during heating and that a simple proportionality between the thermo mechanical strain and free thermal strain suggested by Thelandersson [7] could not be confirmed by Khoury et al. [2] because while thermal strain is related to the aggregate, thermo mechanical strain is related to the cement paste.

The relationship between thermal strain of concrete and temperature is non-linear at higher temperatures due to the transformations in the aggregates and failure of the bond between aggregate and cement paste resulting in increasing coefficients of thermal expansion with increasing temperature. At normal temperatures, hardened cement paste has a higher coefficient of thermal expansion than aggregate and this is because the thermal expansion due to the swelling pressure (caused by a decrease in the capillary tension of water as temperature increases) competes with the thermal shrinkage due to the loss of the evaporable and chemically bound water and conversion of the $Ca(OH)_2$ into CaO to give a net expansion at temperatures of up to about 300^{o}C and a net contraction at higher temperatures [11]. Schneider [12] also reported that the expansion of concrete generally increases with temperature because the expansion in the aggregates usually predominates over the shrinkage in the paste. This is because aggregates constituting about 65-80% of concrete volume would, on heating, lose their evaporable water and undergo transformation or decomposition based on their silica content [11].

The gradual conversion of α-quartz to β-quartz in siliceous aggregates at 500-650^{o}C peaked at about 573^{o}C and would increase expansion in concrete by 1.0-1.4% [11]. To capture the change in behaviour experimentally detected around the transition temperature, Nielsen et al. [1] suggested a combination of two parabolic expressions with a common tangent at the transition temperature with the upper curve agreeing best with the experimental result of Schneider [6] and the lower curve agreeing with the master curve of Khoury et al. [2] and Terro [8] defining a range where the thermo mechanical strain would likely be found for normal concretes with various aggregate types. The coefficient of thermo mechanical strain was also obtained by Nielsen et al. [1] as a function of three parameters A, B and C respectively defined as 0.4x10^{-3}, 1.0x10^{-3} and 7.0x10^{-3} for the upper curve and 0.6x10^{-3}, 1.5x10^{-3} and 10.0x10^{-3} for the lower curve.

The results of the experiments carried out on thermal stresses by Anderberg and Thelandersson [13] at the rates of heating of 1^{o}C/min and 5^{o}C/min over a temperature range of about 20-800^{o}C, within the limit of the critical or failure temperature for a given sustained stress defined by $\frac{\sigma}{f_c^o}$ = -1, is shown in Figure 1. The introduction of the evolution of plastic strains by Khennane and Baker [10] led to the assumption that the temperature dependent compressive strength of concrete at elevated temperatures follows a parabolic expression given by:

$$f_c^T = (1 - 0.016\theta^2)\, f_c^o, \qquad 0 \le \theta \le 7.9 \qquad (1)$$

where f_c^o = initial compressive strength,

T_o = reference temperature, T = temperature and $\theta = \frac{T - To}{100^o C}$. Hence, it is possible to evaluate the critical or failure temperature for a given sustained stress (i.e. when the stress, $\sigma = -f_c^T$ with constant σ).

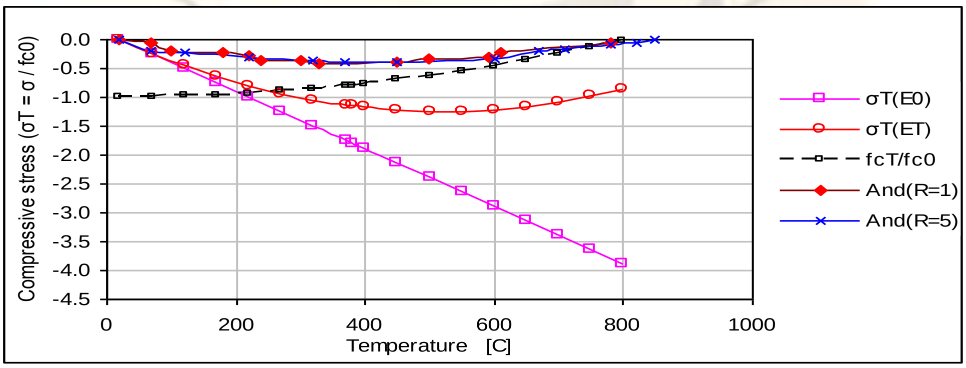

Figure 1: Thermal stresses at 1^o and 5^{o}C/min rate of heating by Anderberg and Thelandersson [13] [And (R= 1) and (R= 5)], stresses based on the initial and degraded modulus of elasticity [σT(E0) and σT(ET)] and temperature dependent compressive stress [-fcT/fc0] of concrete.

The compressive strength of concrete (f_c) decreases with increase in temperature and the residual compressive strength values are lower than the equivalent high temperature strength values [3]. The tensile strength of concrete also reduces with temperature and it is about 1/10th of the compressive strength. Schneider [6] reported that the critical temperature decreases with increasing compressive stress and becomes rapid when f_c exceeds 70-80% of f_c^o. When the applied stress approaches the concrete strength, a significant lateral strain would develop to shift the volume strains from contraction to dilation and the effect of this shift (which appears to happen at stress levels of about 75-85% of the ultimate strength), is modelled using the elastic poisson's ratio below the proportionality limit defined by $0 \geq \sigma \geq -0.5f_c^T$ [1]. Beyond this limit, Poisson's ratio, v, is both temperature and stress dependent, expressed through the third order polynomial:

$$v(T, \sigma) = 0.2 - [25.6(\frac{\sigma}{f_c^T} + 0.5) + 1.6](\frac{\sigma}{f_c^T} + 0.5)^2 \quad (2)$$

arranged so that the value of v = 0.5 is reached for $\sigma = -0.75f_c^T$. Hence, this would define the point where the volumetric strain is assumed to shift to dilation [1].

Poisson's ratio has been observed to drop with heating from about 0.2 at room temperature to about 0.1 at 400°C as a result of bond rupture during heating and cracking which would be much smaller when the heated concrete is restrained or subjected to confining pressure as in nuclear reactor pressure vessels or containment structures where Poisson's ratio would not change because of the high confining pressure [11]. However, while the magnitude of longitudinal and lateral strains were larger for a long-term heated than for an unheated concrete, their ratios were essentially the same [11]. The work of de Borst and Peeters [9] introducing the concept of the transient thermal creep Poisson's ratio and the coefficient of uniaxial thermo mechanical strain, also shows that the transient creep Poisson's ratio which has a magnitude similar to the elastic ratio has proved to be relevant in the modelling of lateral expansion associated with the axial creep under sustained compression.

The modulus of elasticity has been found to be more sensitive to the influences of temperature than strength or any other concrete properties and it reduces with increasing temperature due to bond rupture in paste (when moisture dries rapidly) and increases due to aggregate type [11]. Aside comparing the initial with the degraded modulus of elasticity, Figure 1 shows the variation of the temperature dependent compressive strength [when $\frac{E_o}{f_c^0} = 500$, $E(T) = E_o(1.02\text{-}0.001T)$ and $\alpha = 1\text{x}10^{-5}$] and gives the experimental critical or failure temperature as approximately 800°C.

Hence, when a concrete specimen subjected to heating is restrained against thermal expansion, stress build-up will result. According to Nielsen et al. [1],

- The choice of the thermo mechanical coefficient would have influence on the magnitude of the restraining stress obtained.
- When stiffness is degraded, the non-introduction of the coefficient of thermo mechanical strain would lead to a rapid increase in the restraining stress and the subsequent crushing of the specimen.
- Neglecting degradation by keeping the stiffness constant throughout the heating will give a less significant effect than the introduction of the effect of the thermo mechanical strain.

While normal concretes would suffice at temperatures below 50°C, concretes capable of resisting high temperatures are needed especially in the chemical industry and nuclear reactor structures. Hence, for optimum performance of constructed structures, this paper investigated the transient thermal creep of concrete at elevated temperatures.

2. Research method

This study modelled the experimental results of Ehm [14] and Thelandersson [7] and carried out some investigations using FEAP- Finite Element Analysis Program [15, 16]. Investigations were carried out to determine the effect of degradation of the coefficient of free thermal expansion and modulus of elasticity on the behaviour of concrete at elevated temperatures, the effect of the transient thermal creep on the behaviour of concrete at elevated temperatures and the effect of degradation of sustained compressive stress on the temperature dependent compressive strength of concrete at elevated temperatures.

The methodology involved the generation of 2D plane stress models of unsealed specimens for the steady state and transient state situations using the values of the properties obtained from experiments based on Portland cement concrete. The analysis was basically uniaxial and subject to the following assumptions:

- The creep strain is insignificant so that the load induced thermal strain could be equated to the thermo mechanical strain.
- The elastic Poisson's ratio was used as the transient creep Poisson's ratio based on the assumption that there is no much disparity between the two within the proportionality limit of a sustained compressive stress of 50% of the strength of concrete.
- The effect thermo mechanical strain was based on the upper parabolic curve suggested by Nielsen, et al. [1].

A plane stress concrete model 0.1m x 0.1m x 0.1m was used with the following parameters: initial modulus of elasticity EO = $30x10^9$, poisson's ratio = 0.2, compressive strength (normal concrete), f_c = $30x10^6$, density = 2400, tensile strength = $3x10^6$ ($1/10^{th}$ of compressive strength), coefficient for transient thermal creep defined by A = $0.4x10^{-3}$, B= $1.0x10^{-3}$, C = $7.0x10^{-3}$ which were the upper bound values for the parabolic model proposed by Nielsen et al. [1] based on the experimental results of Schneider [3], coefficient of thermal expansion = $1x10^{-5}$, reference temperature T_o = 293K (20^{o}C) and a total compressive load of 0.01 kN applied at the two upper nodes. Using the time loop of 80 and starting with a time step of 0, the force loads and proportional loads for temperature were obtained in accordance with the FEAP programme for the steady state and transient state models.

The modelling procedure involved developing data files for the cases being investigated, executing them by the FEAP file and comparing the results obtained with the experimental results. Except for the variation in the level of sustained stress, all the models were investigated with a sustained compressive load of 50%f_c. Also, except for the 'no load' situations (used to model the effect of thermally induced stresses only), all the cases were subjected to a total load of 0.01 kN.

The first objective, the investigation of the effect of degraded coefficient of free thermal expansion and modulus of elasticity on the behaviour of concrete at elevated temperatures, was modelled by investigating the effect of the degradation or otherwise of these parameters, with reference to the total axial strains or the restraining stresses over the temperature range. The combinations of the parameters used were

- When both the coefficient of thermal expansion and the modulus of elasticity remain constant (i.e. undegraded by temperature).
- When either the coefficient of thermal expansion or the modulus of elasticity remains constant and the other degraded by temperature.
- When both the coefficient of thermal expansion and the modulus of elasticity were degraded by temperature.

The restraining stress was modelled by applying zero initial stress on the concrete specimen when it is restrained against thermal expansion. The combinations of the material parameters were investigated for the strain and stress cases and the restrained stresses were compared with the experimental result of Ehm [14] which was also carried out with a zero initial stress.

The second objective, the investigation of the effect of transient thermal creep or load-induced thermal strain (i.e. the inclusion of the effect of thermo mechanical strain) on the behaviour of concrete at elevated temperatures, involved comparing the result of the restraining stresses obtained without the inclusion of the effect of thermo mechanical strain with the result obtained with the inclusion of the effect of thermo mechanical strain when the coefficient of thermal expansion and the modulus of elasticity were both degraded by temperature.

The third objective is the investigation of the effect of sustained compressive stress on the temperature-dependent compressive strength of concrete at elevated temperatures, involved investigating and comparing the total axial strains obtained at some selected stress levels with the experimental results of Thelandersson [7]. The stress levels investigated were 0%, 22.5%, 45% and 67.5% of the compressive strength of concrete used by Thelandersson [7].

3. Discussion of Results

3.1 Effect of degradation of material properties without the inclusion of thermo mechanical strain

The effect of the degradation of the coefficient of free thermal expansion and the modulus of elasticity on the behaviour of concrete for the steady state and transient state specimens are presented in Figures 2-4. These results were based on the application of a total sustained compressive load of 0.01 kN at the two upper joints of the plane stress model. Figure 2 shows that when the coefficient of free thermal expansion and the modulus of elasticity were assumed undegraded at elevated temperatures, linear relations result between the strains and temperatures for both the steady state and transient state specimens. Since this result does not model the expected experimental results, it could be concluded that when concrete is subjected to elevated temperatures there is the likelihood that the coefficient of thermal expansion and the modulus of elasticity would be degraded.

Figure 3 shows that when the coefficient of thermal expansion was assumed degraded and the modulus of elasticity was assumed undegraded, non-linear relation results between strain and temperature, for the steady state and transient state specimens, with the strain rate increasing with increase in temperature up to a temperature of 893K (600°C). No change in strain was recorded between 893K and 993K (700°C). This model prediction therefore supports the experimental results which states that between 600 and 800°C, concrete does not expand due to the chemical and physical changes occurring in the aggregates and the hardened cement paste. This result also confirms that the coefficient of thermal expansion would be degraded when concrete is subjected to elevated temperatures.

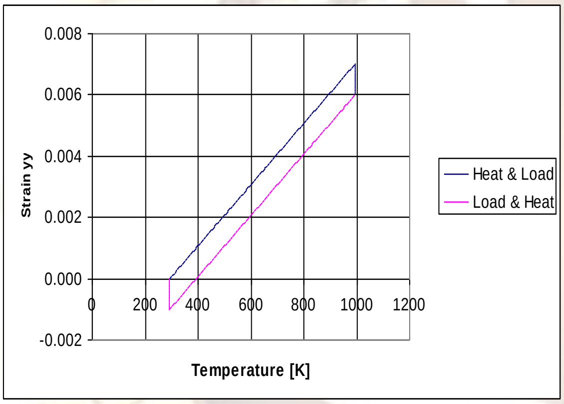

Figure 2: Strain in concrete when coefficient of thermal expansion and modulus of elasticity are undegraded

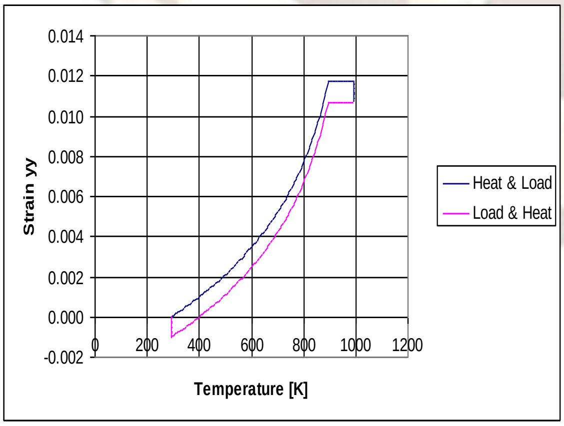

Figure 3: Strain in concrete when coefficient of thermal expansion is degraded and modulus of elasticity is undegraded.

Figure 4 shows that when the coefficient of thermal expansion and modulus of elasticity were degraded, the steady state model does not show the effect of the degradation of the stiffness on the strain in concrete until the application of the load at 993K when a further decrease in thermal strain, with reference to Figure 3, was observed under the load. However, the result of the transient state model shows that the effect of the degradation of the stiffness was observed early during the heating phase leading to a decrease in the thermal strain at an increasing rate with increase in temperature up to 893K (600°C) due to the reduced longitudinal expansion (and increased lateral expansion) as a result of loss of stiffness. 600°C could therefore be taken as the critical temperature for failure. It was also observed that expansion or contraction did not cease between 600 and 700°C, as observed in Figure 3. Instead contraction occurred in the longitudinal direction leading to a further decrease in strain (associated with further increase in lateral strain) and the likelihood of failure.

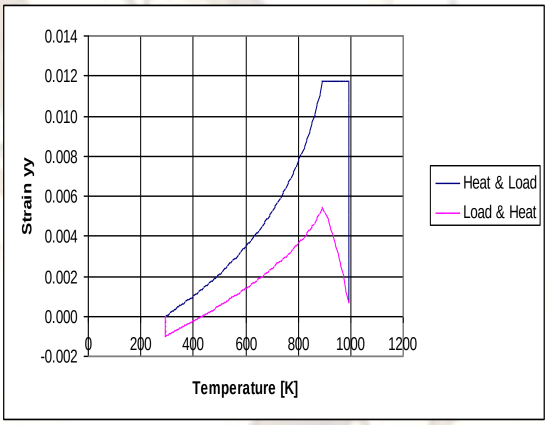

Figure 4: Strain in concrete when coefficient of thermal expansion and modulus of elasticity are both degraded.

It could therefore be concluded that when a concrete member, under sustained load, is subjected to elevated temperatures, both the coefficient of thermal expansion and the modulus of elasticity would be degraded and failure would soon be reached. It could also be inferred that a steady state experiment may not be the best for assessing the behaviour of concrete members subjected to elevated temperatures.

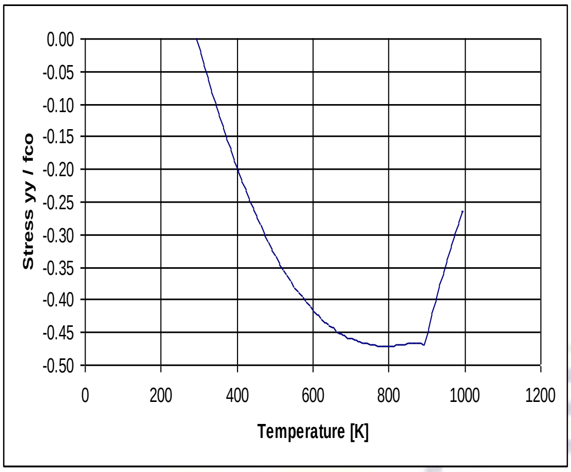

Figure 5: Restraining stress at zero initial stress without the effect of thermo mechanical strain.

Figure 5 shows the result obtained when the restraining stress was modelled, at a stress level of $0.5f_c$, without the inclusion of the effect of the thermo mechanical strain and with the assumption that both the coefficient of thermal expansion and the modulus of elasticity were degraded. This result shows a higher stress build-up and more susceptibility to failure than when the effect of the thermo mechanical strain was introduced (Figure 6).

3.2 Effect of the degradation of material properties with the inclusion of thermo mechanical strain

The results of the modelling, with a sustained compressive stress of $0.5f_c$, with reference to the coefficient of thermal expansion and the modulus of elasticity are presented in Figures 6 and 7. Figure 6 shows the effect of the parameters with reference to the dimensionless restraining stress while Figure 7 compares the model predictions with the experimental result of Ehm [14] which was based on a rate of heating of 2°C/min and zero initial stress.

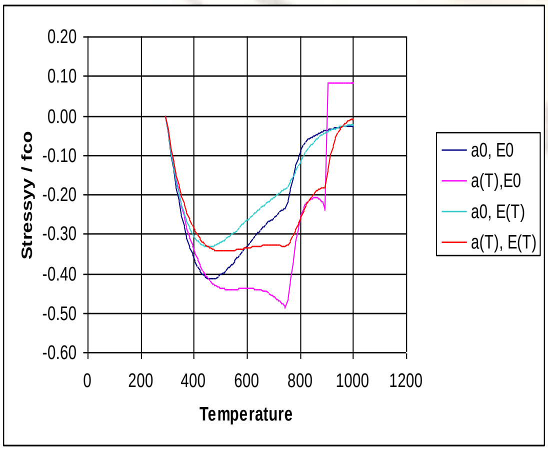

Figure 6: Restraining stress at zero initial stress with thermo mechanical strain effect for different combinations of constant (a0/E0) and degraded (aT/ET) coeff. of thermal expansion/modulus of elasticity

Figure 6 shows that

- Neglecting the degradation of the coefficient of free thermal expansion and considering the degradation of the modulus of elasticity, up to a temperature of 777K (504°C), would give the most significant effect when modelling the behaviour of concrete at elevated temperatures. It is also shown that after 504°C, the effect of the degradation of the modulus of elasticity becomes less significant. This is probably due to the change in the coefficient of the thermo mechanical strain at 470°C as stated below.
- Neglecting the degradation of both the coefficient of thermal expansion and modulus of elasticity would be better than considering both in their degraded states, vice-versa, when modelling the behaviour of concrete above a temperature of 588K (315°C). It is also shown that below this temperature it would be better to consider the degradation of the modulus of elasticity than considering the degradation of both the coefficient of thermal expansion and the modulus of elasticity.
- Considering the degradation of both the coefficient of thermal expansion and modulus of elasticity throughout the period of heating is better than considering the degradation of the coefficient of thermal expansion and neglecting the degradation of the modulus of elasticity.

From the premises above, it therefore follows that under a sustained compressive load of not more than 50% of the compressive strength of concrete, the degradation of the coefficient of thermal expansion and the modulus of elasticity could be neglected throughout the duration of heating when modelling normal concretes at elevated temperatures. It is also shown that the consideration of the degradation of the modulus of elasticity is paramount over the consideration of the coefficient of thermal expansion when modelling normal concretes at elevated temperatures.

Figure 6 also shows that distinct changes occurred in the material properties at temperatures of 742K (469°C) and 892K (619°C). Based on the discussion above, the first transition temperature would be linked with change in the coefficient of thermo mechanical strain while the second would be linked with change in the coefficient of thermal expansion. A critical observation of these curves also gives an insight into what would happen during the cooling of a concrete specimen from elevated temperatures. The curves show that on cooling, following the opposite path to the path obtained during heating, tensile phase would soon be reached and the build-up of tensile stresses would lead to the cracking and subsequent fracture of the specimen. This is so because the magnitude of the tensile strength of concrete is about 1/10th of its compressive strength.

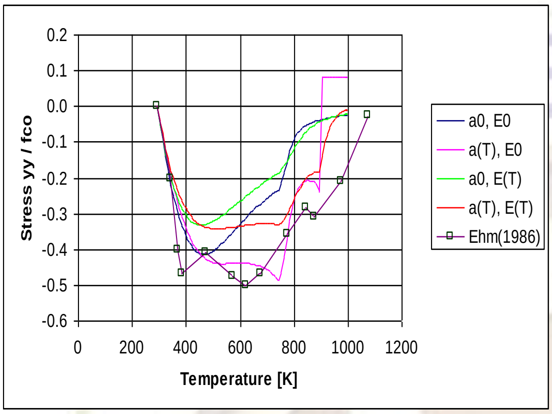

Figure 7: Restraining stress at zero initial stress with thermo mechanical strain effect for different combinations of constant (a0/E0) and degraded (aT/ET) coeff. of thermal expansion/modulus of elasticity compared with the experimental results of Ehm [14].

Figure 7 shows that while the experimental stress peaks are more pronounced and shifted along the temperature axis, the model prediction still qualitatively capture the experimental results of Ehm [14]. This may be due to the likely disparity in the values of the coefficients of thermal expansion and thermo mechanical strain or the non-inclusion of the hygral effects, known to be strong at temperatures up to 200°C.

3.3 Effect of transient thermal creep on the behaviour of concrete at elevated temperatures

To model and investigates the relevance of the transient thermal creep (or load-induced thermal strain) in concrete at elevated temperatures, the effect of thermo mechanical strain was introduced on the result obtained in Figure 4. While the introduction of the effect of thermo mechanical strain on the steady state model gave the same result as in Figure 4, the effect of thermo mechanical strain on the transient state model (Figure 8) shows that concrete will be in compression all through and the likelihood of tensile failure or fracture would be ruled out. Hence, the effect of thermo mechanical strain was not felt on the steady state model. This is simply because the load induced thermal strain is not a component of the total strain under a steady state. It could therefore be concluded that the load induced thermal strain is very relevant when considering the prevention of tensile failure in concrete, under sustained load, at elevated temperatures.

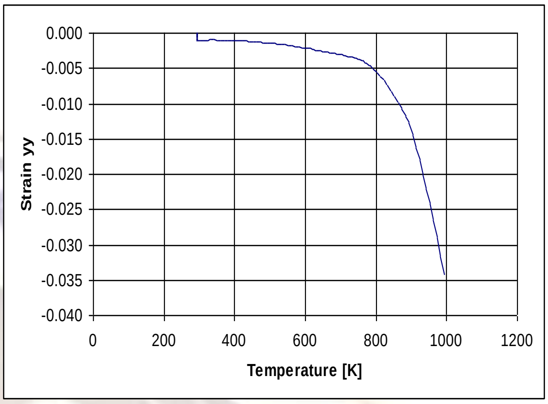

Figure 8: Total axial strain for transient state model, at 50%f_c sustained compressive stress with the effect of thermo mechanical strain.

3.4 Effect of sustained compressive load on the temperature dependent strength of concrete at elevated temperatures

Figures 9 and 10 show the effect of thermo mechanical strain on the steady state models while Figures 11 and 12 show the same effect on the transient state models for varying levels of sustained compressive stress. Figure 9 shows the result for the 22.5% stress level while Figure 10 shows the result for the 67.5% stress level. While the result for the 0% stress level is the same as for the 0% stress level for the transient state model (Figure 11), the result for the 45% stress level which is an 'in-between' between the results for 22.5% and 67.5% levels is not illustrated. The results for the steady state models show free thermal strain and do not reflect the effect of the inclusion of the thermo mechanical strain. This is due to the fact that there is no load-induced thermal strain in the steady state situation.

The results of the transient state models, excluding the case of 'no load' which is not strictly a transient state model, show the presence of the load-induced thermal strain. These results also show that the model predictions, though with varying degrees of disparities (Figure 12), could be said to fit the experimental results of Thelandersson [7]. These disparities could be linked with the disparity in the critical temperature of 710°C predicted by the parabolic expression used in this modelling as against the temperature of about 800°C obtained experimentally (Figure 1) for the temperature dependent compressive strength of concrete.

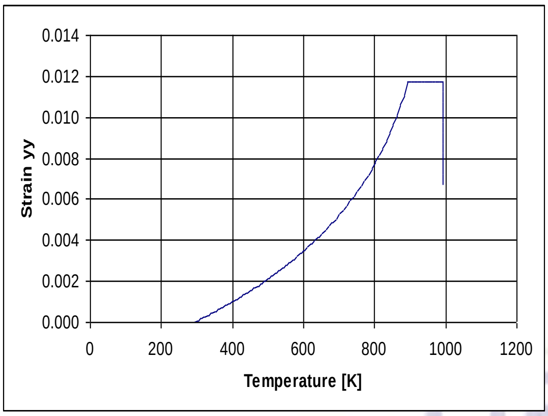

Figure 9: Total axial strain for the steady state model at 22.5%f_c sustained compressive load with the effect of thermo mechanical strain.

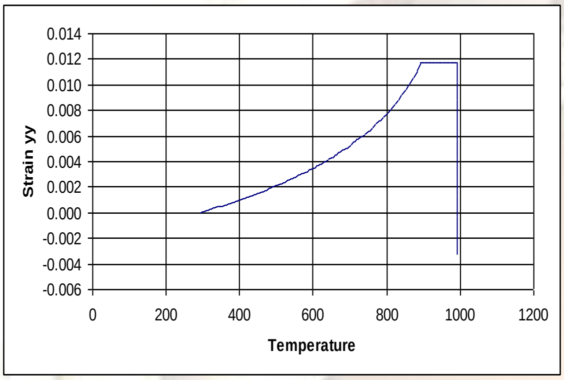

Figure 10: Total axial strain for steady state model at 67.5%f_c sustained compressive load with the effect of thermo mechanical strain.

Figure 12 also shows that there is a better fit between the model predictions and the experimental results for the cases of free thermal strain (or 0% compressive stress) and 67.5% compressive stress. The lack of proper fit for the cases of 22.5% and 45% compressive stress, at later temperatures, could be due to the fact that this modelling assumes the elastic poisson's ratio to be constant below the stress proportionality limit defined by $0 \geq \sigma \geq -0.5f_c^T$ based on the scope of this work. The transient state results (Figure 11) also shows that the critical temperature decreases with increase in the magnitude of the compressive stress. This therefore implies that failure will soon be reached with increasing load.

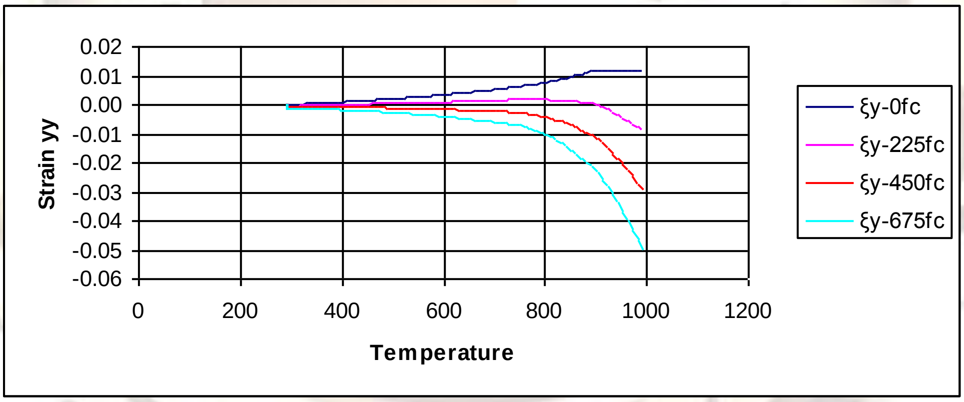

Figure 11: Total axial strain (ξy) for transient state model at 0%, 22.5%, 45% and 67.5%$f_c$sustained compressive stress with the effect of thermomechanical strain.

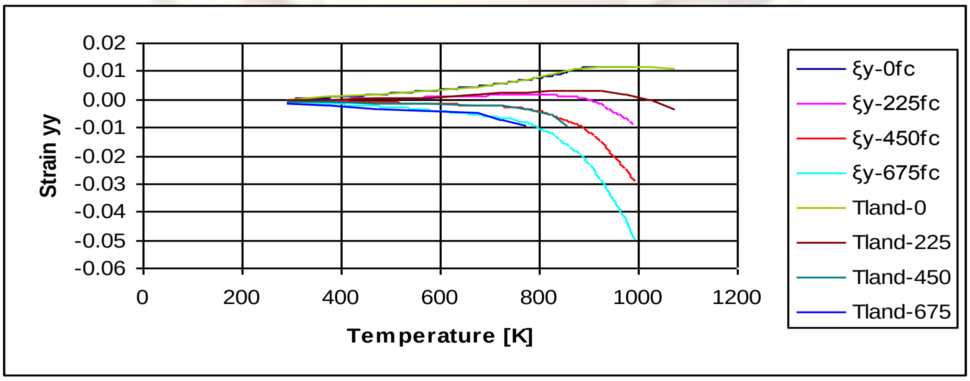

Figure 12: Total axial strain (ξy) for transient state models compared with the experimental results of Thelandersson [7].

4. Conclusion

The modelling of the effect of transient thermal creep in concrete at elevated temperatures has been carried out with FEAP within the range of 293K (20^{o}C) and 993K (700^{o}C) with the assumption that transient thermal creep (load-induced thermal strain) is equivalent to thermo mechanical strain. This is because the conventional creep strain is less significant when compared with the thermo mechanical strain under most conditions. The following have therefore been concluded from the study.

This study confirmed the non-existence of the effect of transient thermal creep in steady state specimens and the degradation of the coefficient of free thermal expansion and modulus of elasticity of the material at elevated temperatures. The study shows that under a sustained compressive load of not more than 50% of the compressive strength of concrete and the effect of thermo mechanical strain, the degradation of the coefficient of thermal expansion and the modulus of elasticity could be neglected throughout the period of heating when modelling normal concrete at elevated temperatures. It is also shown that the degradation of the modulus of elasticity is more significant than the degradation of the coefficient of thermal expansion when modelling concrete at elevated temperatures. It has also been confirmed that a change occurred in the coefficient of thermal expansion at a temperature of 619^{o}C which is close to a temperature of 620^{o}C obtained by Nielsen et al. [1].

The model predictions fit the experimental results of Ehm [14] and Thelandersson [7] and therefore could be extended to predict some other parameters on which few or no experimental results exist. For example the results of the axial strains obtained through FEAP are accompanied by the lateral strains on which very few experimental results exist. The possibility of the availability of lateral strain data, at various temperatures, could also give an insight into the behaviour of the Poisson's ratio of concrete at elevated temperatures.

Thermo mechanical strain has been confirmed to have the ability to relax the stresses arising from thermal gradients and incompatibilities between the aggregates and cement paste during heating. It has been confirmed that a change occur in the coefficient of thermo mechanical strain at a temperature of 469^{o}C which is also close to a temperature of 470^{o}C obtained by Nielsen et al. [1]. It was also observed that the build-up of tensile stresses could occur during cooling and this has been attributed to the irreversibility of the thermo mechanical strain [5]. Finally, the study showed that the critical or failure temperature of concrete, at elevated temperatures, decreases with increase in the magnitude of the sustained compressive stress. This therefore shows that failure will soon be reached with increasing sustained stress.

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