TEMPERATURES AND STRAINS IN HARDENED CONCRETE BEAMS SUBJECTED TO A CLIMATE SIMILAR TO THAT OF CENTRAL SAUDI ARABIA

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الخلاصة :

«الحرارة والإنفعال في كمرات الخرسانة عند تعريضها إلى مناخ مشابه لمناخ المنطقة الوسطى في المملكة العربية السعودية» ، تأليف : ع . س . رواف ، أ . ر . سلبي .

مناخ المنطقة الوسطى في المملكة العربية السعودية يعتبر حار وجاف في الصيف وبارد في الشتاء خاصة في ليالي الشتاء . في هذا البحث أستخدم التحليل العددي المبني على درجات الحرارة وأشعة الشمس لإيجاد توزيع الحرارة داخل كمرات خرسانية بأعمقة مختلفة . لقد إستنتج من مجموعة تجارب على كمرات محملة ومعرضة لدوريات يومية من قيم درجات حرارة عالية ودرجات رطوبة منخفضة أن الإنفعال الناتج من التوزيع الحراري يتفق بشكل جيد مع القيم المحسوبة . كما وجد كذلك أن تعرف الكمرات المختومة عن تسرب الندى بشكل جزئي أو غير جزئي وكذلك الغير مختومة ليس بالسهل ولكنه معقد للغاية . التكييف الدوري (ارتفاع الحرارة وانخفاض الرطوبة) يسبب ارتفاع في قيم الزحف والإنكماش في الأيام الأولى ولكن هذه القيم تقل كثيراً عندما تقترب الخرسانة من الجفاف . هذا يوضح أن الزحف لا يزداد دائماً مع الحرارة . في هذا المناخ التأثير الأساسي على الخرسانة هو تغير الندى داخل الخرسانة نتيجة للقيم المنخفضة لدرجة الرطوبة .

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ABSTRACT

The climate of central Saudi Arabia is hot and very dry in summer, with cold winter nights. Temperature profiles are predicted in shallow and deep concrete slabs by numerical analysis based on air temperatures and solar radiation. In a series of tests on loaded beams exposed to daily cycles of high temperatures and low humidity, the strains arising from the temperature profiles agreed closely with predicted values. The longer term deformations of the unsealed, partly sealed and fully sealed beams were complex. The daily environmental cycling tended to cause high early age creep and shrinkage but lower later values as the concrete approached desiccation. This shows that creep is not always increased by higher temperatures. In this climate the dominant effect upon concrete is moisture change caused by the low humidity.

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INTRODUCTION

The climate of central Saudi Arabia is typical of a tropical desert region, with high levels of shade air temperature and of solar radiation during spring and summer days combined with very low values of relative humidity. Spring nights are cool and winter nights are cold.

The problems of casting concrete in such conditions are well recognised, and recommendations are made in [1]. However, extreme conditions will cause large strains and stresses in hardened concrete beams due to thermal changes, and strains due to creep and shrinkage may be modified.

The consequences upon durability of unexpectedly large thermal stresses, axial strains and curvatures can be severe, with degradation apparent as substantial cracking, or as unacceptable deformations which cause damage to supporting or supported components. Cladding units frequently suffer cracking and spalling due to constraint by their fixings; the building frame, under fairly constant temperature and humidity, shows little dimensional change, but the temperature of the external face of the cladding panel can be expected to vary by some 20°C in a day and by 50°C per year and the fixings must be able to tolerate the consequential expansion and curvature changes. Similarly, roof slabs and bridge decks will have daily and yearly cycles of top surface temperatures, which will cause thermal strains and curvatures, and these must be tolerable to the supporting structure; precast units sitting directly upon brickwork or on concrete ledges may cause progressive deterioration due to the daily cycle of thermal movements; thermal gradients imposed onto continuous beams cause redistribution of support forces (and secondary moments) so that the end supports may be overloaded. Thermal stresses may be superimposed upon working load stresses to aggravate cracking which may lead to earlier deterioration. Similarly, unexpectedly large shrinkage or creep deformations may cause cracking, damage, or separation between beams and partitions or cladding/glazing units. In addition, potential reduction in durability may result from cycles of temperature gradients in terms of lower ultimate strength and increased permeability, although evidence of these effects is very limited. Also, elevation of the surface temperature from 20°C to 70°C might be expected to cause a substantial acceleration of surface carbonation, resulting in a more rapid depassivation of the reinforcement.

Firstly, temperatures in some concrete slabs are predicted by finite element analyses based upon meteorological records for Riyadh. From these temperature profiles, predictions are made of curvature, axial strain, and locked-in stresses, in concrete sections both uncracked and cracked by imposed moment.

Secondly, results are presented from an extensive series of tests on beams subjected to diurnal environmental cycles of high air temperatures, high solar radiation, and low humidity. The beams were tested with varied conditions of surface sealing, such as side faces sealed to represent a portion of slab, and top faces sealed to model a waterproofing membrane. Beam responses to the diurnal environmental cycle showed close agreement with a simple iterative numerical analysis. Shrinkage curvatures were substantial in singly-reinforced beams, but were greatly modified by the conditions of sealing. Creep strains in beams in the diurnal environmental cycles developed rapidly in the primary stage but were then reduced, so that overall creep was similar to that in beams in a 'normal' environment.

TEMPERATURES IN CONCRETE SLABS

Three conditions are considered, of maximum absolute top surface temperature, of maximum temperature difference, and of maximum reversed temperature difference (such as occurs at the end of a cold night), for plain concrete surfaces and for black-painted top surfaces representing water-proofing. The maximum absolute temperatures are of interest with respect to possible future work studying accelerated deterioration through carbonation or chloride or sulfate attack. The maximum positive temperature difference is relevant to locked-in compressive surface stress and to large axial expansive strains and upward curvatures in a simply-supported member. The reversed temperature profiles relate to locked-in tensile stress at the surfaces, to sag curvature, and to axial shortening.

In calculations of temperatures in a horizontal slab, the dominant environmental factors are the air temperatures above and below the slab (usually taken to be the shade air temperature) and the solar radiation. Meteorological records [2] for Riyadh give a maximum range of air temperatures in late spring of 15/45°C over a 15 year period. The highest shade air temperature in summer was 49°C. It is assumed, following the practice of Emerson [3], that air temperature variation is linear between a minimum at 0500 hours and a maximum at 1500 hours, local time. Predictions of maximum temperature differences are based on temperatures of 15° and 45°C, absolute maximum temperatures are based on 34° to 50°C, and reversed profiles are based upon 1° to 20°C representing a cold winter night.

Solar radiation, I, during a late spring/early summer day is defined approximately, at time t, by

$$I(t)=\frac{2S}{T}\sin^2\frac{\pi t}{T}$$

which is an equation used successfully for conditions in the UK, where a longer day, T, is experienced with lower total radiation, S. In Riyadh, the peak value of total radiation, S, is about $8600\,\mathrm{Wh\,m^{-2}}$. Radiation loss to a night sky is fairly constant at about $-130\,\mathrm{W\,m^{-2}}$. Absorptivity is taken to be 0.5 for plain concrete, and 0.85 for a black-painted surface, and emissivity to be 0.9 for either surface.

Surface heat transfer coefficients are assumed to be $23\,\mathrm{W\,m^{-2}\,°C^{-1}}$ and $9\,\mathrm{W\,m^{-2}\,°C^{-1}}$ for upper and lower surfaces in daytime, and $19\,\mathrm{W\,m^{-2}\,°C^{-1}}$ and $2\,\mathrm{W\,m^{-2}\,°C^{-1}}$ at night. Thermal diffusivity of concrete is taken as $0.6\times10^{-6}\,\mathrm{m^2\,s^{-1}}$ and is assumed to be representative of concrete as a homogenous material. Many of these values are quoted in [3].

Thermal analysis by finite element of 200 mm and 600 mm slabs for the above conditions, as previously described, [4], gives temperature profiles through the slab thicknesses as shown in Figure 1. Temperatures of up to 71°C are predicted, which is in good agreement with a peak measured value of 73°C reported by Potocki [5]. The largest temperature differences are 33°C and −15°C.

DIURNAL THERMAL STRAINS AND STRESSES

The consequences of the existence of a nonlinear temperature profile are exemplified in Figure 2, for the condition of an uncracked concrete member free to allow axial expansion and curvature. The increase in

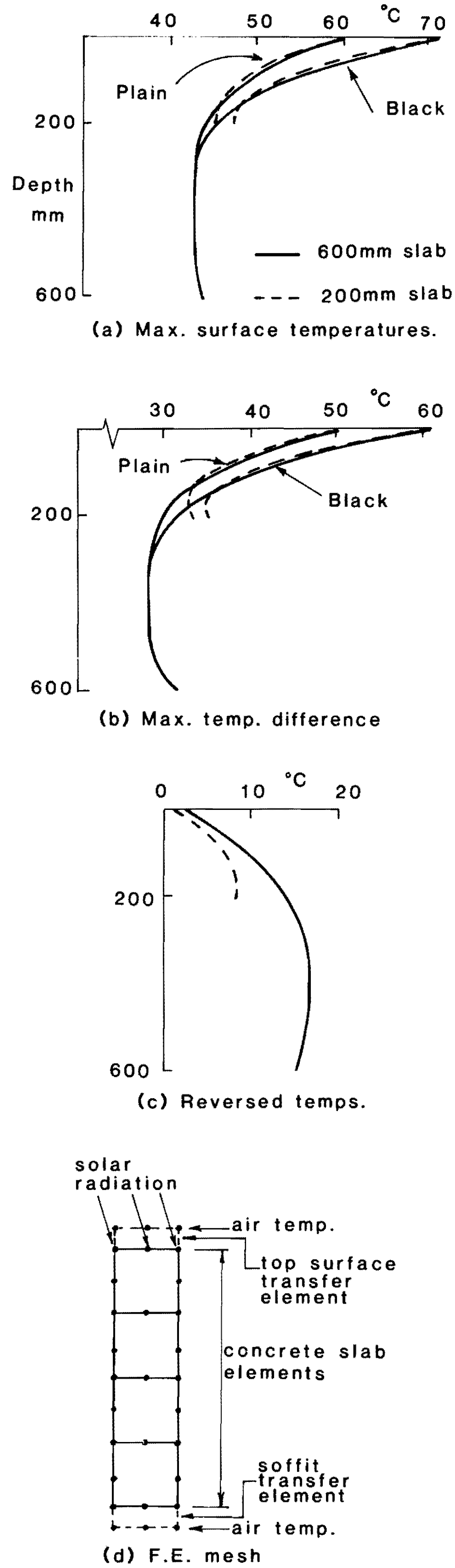

Figure 1. Temperature Profiles

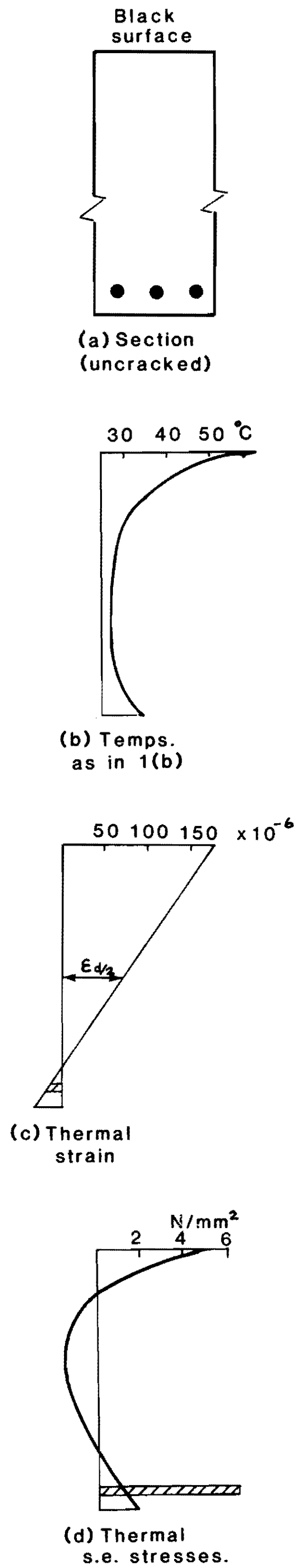

Figure 2. Response to a Temperature Profile

average temperature induces axial expansion, the bias of temperature increase near to the top surface causes hog curvature, and the sum of these two components is the thermal strain diagram 2(c). The non-linearity of the profile implies locked-in thermal self-equilibrating stresses as shown in 2(d). If there is total or partial restraint to either axial strain or curvature then additional stresses would arise. Continuous beams offer partial moment restraint causing thermal moments, and redistribution of support forces.

Analysis of a reinforced concrete section, cracked or uncracked, is easily achieved by computer program, following the equilibria conditions outlined by Hambly [6]. Results for the 200 mm and 600 mm slabs singly reinforced with 1% steel area, are given in Table 1. Analysis of the slabs by cracked or uncracked criteria shows little differences in either curvature or in axial strain, but stresses are more affected. Thermal response of the 200 mm thick slab, both in axial strain and curvature, is considerably larger than in the 600 mm slab, but self-equilibrating stresses are much larger in the deeper slab.

In order to assess the significance of the thermal strains, consider a 3 m span one-way slab, subjected to a diurnal cycle resulting in curvature of $0.86 \times 10^{-6}\,\mathrm{mm}^{-1}$ and axial strain of 0.13×10^{-3}. Axial expansion will be 0.4 mm, and hog deflection due to the curvature will be 1 mm. Neither movement should cause any problem, unless the member is intimately connected to brittle brickwork or glazing panels.

The stresses induced in the deep slab, of up to $4.3\,\mathrm{N\,mm^{-2}}$ compressive, $0.9\,\mathrm{N\,mm^{-2}}$ tensile, in susceptible surfaces, appear to be severe, at first sight. Analysis demonstrates that cracking may be aggravated, or even initiated, when thermal stresses combine with loading. However, as White [7] points out, ultimate limit state conditions are not affected by the thermal loading, since the thermal *strains* are only a small percentage of failure strain. A very limited test program has been undertaken [8], which suggests that thermal cycling may cause increased permeability, leading to reduced durability, but more work is required on this problem.

In conclusion, concrete members exposed to diurnal temperature profile cycles show only small deformations. However, self-equilibrating stresses are large, and while they do not affect the ultimate resistance of the section, durability may be reduced both by increased cracking and by increased permeability due to cycling of temperature profiles.

Table 1. Effects of Non-Linear Temperature Profiles

Case	Section cracked	Thermal curvature $1/R \times 10^6$ mm^{-1}	Mid-depth axial thermal strains $\varepsilon_{d/2} \times 10^3$	Thermal stresses		
				σ_t	$\sigma_{d/2}$	σ_b
200	N	0.86	0.13	7.05	−0.60	0.90
(plain)	Y	0.94	0.135	0.70	—	—
200	N	1.36	0.19	1.36	−0.77	1.17
(black)	Y	1.47	0.20	0.90	—	—
200	N	−0.40	−0.13	−0.40	0.33	0.24
(reversed temperature)	Y	−0.40	−0.14	−0.30	—	
600	N	0.21	0.048	3.0	−1.04	1.2
(plain)	Y	0.23	0.061	2.5	—	—
600	N	0.35	0.073	4.3	−1.5	1.7
(black)	Y	0.39	0.090	3.6	—	—
600	N	−0.19	−0.054	−1.6	−0.9	0.8
(reversed temperature)	Y	−0.21	−0.059	−1.4	—	

EXPERIMENTAL PROGRAMME

A number of tests was undertaken to study the behavior of concrete beams exposed to both physical loading and to the diurnal environmental cycle. The beams were 2800 × 100 × 200 mm deep, singly-reinforced, and in various conditions of surface sealing, being sealed on all surfaces, on top and side faces (partly sealed), or completely unsealed. Beams cast from a standard 1:2:4 mix were cured for two weeks. The coarse and fine aggregates were Scorton river gravel, predominantly sandstones, the cement was O.P.C. and the water cement ratio was 0.50. They were then surface sealed (if appropriate) with three coats of epoxy-based paint. Gauge points were attached, and the beams were then prepared for loading and environmental cycling at an age of 21 days.

In each test, see Table 2, two beams were physically loaded, back-to-back in a weights-and-levers rig which gave stable long-term four-point loading. (Figure 3). The tests were conducted inside an environmental chamber, so that air temperature and relative humidity could be cycled daily to follow values appropriate to the spring or summer climate of Riyadh. Relative humidity of the air in the chamber was reduced by means of a vessel containing several layers of activated silica gel crystals. A fan forced air through the vessel for the appropriate duration in each day, with reactivation between times by heating elements. Values of relative humidity were reduced to 10%, which is characteristic of Riyadh conditions. Heating of the air was by electric fan heaters. Cooling of the air in the chamber, to model spring night conditions, was achieved by circulation of water and glycol, cooled in

Table 2. Summary of Test Program

Test code	Section cracked?	Sealed faces	Air temps, °C	Min. humidity %	Surface temps. °C	Applied moment kN m
5I*	N	Top and sides	30–50	13	30–62	4.03/3.3
5II	N	Top and sides	30–50	13	30–62	4.03/3.3
5III*	Y	None	30–50	13	30–62	6.10/5.53
6I	Y	None	9–45	10	9–64	6.10/5.53
6II	Y	Top and sides	9–45	10	9–64	6.10/5.53
6III	Y	All faces	9–45	10	9–64	6.10/5.53
7Ia	Y	Top and sides	20 ± 1	50 ± 5	20	6.10
7Ib	Y	None	20 ± 1	50 ± 5	20	5.53

*Beams loaded physically prior to heat cycling

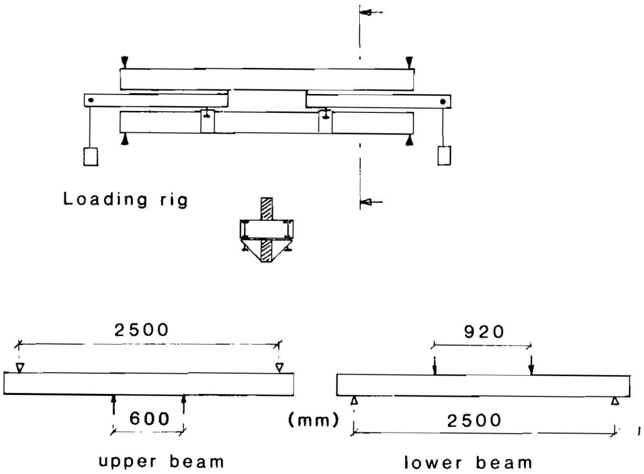

Figure 3. Four-Point Bending of Beam Pair

a compressor-driven chiller unit, through fan-assisted heat-exchanger coils. Air temperatures of between 5° and 10°C were achieved, causing reversed temperature profiles similar to, but less severe than, that in Figure 1c. Solar radiation gain was modelled by the use of electrical heating tape laid on the top surface of one of the beams. Two additional unloaded beams, 1000 x 100 x 200 mm deep were tested in similar environmental conditions, to allow separation of creep and shrinkage deformations.

Temperatures in all the beams were measured by thermocouples embedded in the concrete during casting. Strains were recorded on the side faces of the beams by a demountable mechanical gauge, which had the advantage over electrical resistance or vibrating wire gauges of reading total thermal strain without temperature correction. Many additional reference specimens were tested for strength, stiffness, uniaxial constant-temperature creep, and coefficient of thermal expansion. Further details are given in [9].

TEST RESULTS

Control of the conditions in the environmental chamber was sufficient to achieve each day a realistic temperature profile, closely similar to the predicted profile for a black surface concrete slab, 200 mm thick, as shown in Figure 1b. The heating tape model of solar radiation was particularly effective: the total summer time radiation between 0800 and 1500 hours, factored by absorptivity is 3500 W, while the energy supplied by the heat tape during an equivalent period was measured to be 3600 W. The start of the heating cycle in the laboratory was at 09.00 hours (1 hour later than real-life conditions) and maximum concrete surface temperatures were reached by about 13.00 hours. The heating cycle was terminated at 17.00 hours, with in 'summer' a 16 hour recovery to start of cycle conditions; in 'spring' the cooling system was switched on at 18.00 hours, achieving minimum temperatures by about 05.00 hours.

Comparison of measured strains and curvatures during the daily cycle over a very large number of tests with predictions by the iterative computer analysis showed consistent close agreement to within 15%, except during the first and second days after loading when rapid primary creep caused much wider differences. The choice of value of coefficient of thermal expansion was critical to good agreement. Measured values ranged from 10.4×10^{-6} °C^{-1} to 12.7×10^{-6} °C^{-1}, dependent upon the level of gel water in the specimen at the time of testing. Provided that a realistic estimate of the coefficient can be made, then thermal strains in the concrete beams can be predicted to better than 10% accuracy. Predictive values of thermal strains in Table 1 suggest that response of a beam to the daily temperature profiles is relatively insensitive to whether the beam is cracked or uncracked. This was clearly demonstrated in tests, with almost identical thermal strains being shown by cracked and uncracked beams (except during primary creep).

Long term strains measured in the concrete beams will be discussed in terms of immediate deflections, shrinkage curvature and of creep curvature. Whilst shinkage was of interest, response was generally small, and concentration was centered upon creep.

Immediate deformations of beams in response to loading were reduced by exposure to the severe environment of high cyclic air temperatures and low humidity (Table 2) for several days prior to loading if the beam were totally or partly sealed, since accelerated hydration occurred. Conversely, unsealed beams exposed to this environment showed larger immediate deformations because the low humidity caused rapid moisture movement and loss, to the detriment of hydration. See, for example, some results of beams, 2800 x 200 x 100 mm, loaded in 4 point bending and heated for 3 days prior to loading, Table 3. Beam 5.III.2 shows a 35% increase in immediate deformation over 6.III.2, and 5.III.4 shows a similar increase over 6.III.4.

Axial shrinkage of the beams under test was very small, being typically about 200 $\mu\varepsilon$ between days 21

Table 3. Examples of Immediate Deflections

Beam code	Sealing	Moment	Central curvature	Central deflection
5.III.2	Unsealed	6.1 kN m	7.4×10^{-6} mm^{-1}	4.98 mm
5.III.4	Unsealed	5.53 kN m	6.1×10^{-6} mm^{-1}	3.83 mm
6.III.2	Totally sealed	6.1 kN m	5.4×10^{-6} mm^{-1}	3.69 mm
6.III.4	Totally sealed	5.53 kN m	4.5×10^{-6} mm^{-1}	2.82 mm

and 60, and is not discussed further. Shrinkage curvature of unsealed singly-reinforced beams was in sag mode, and beams in the severe summer environment showed some 60% more sag curvature than the beams in laboratory conditions. Figure 4. Beams sealed on top and side faces showed initial hogging shrinkage as only the lower face lost water, but with longer term tendency towards sagging. The maximum hog was similar in beams in the severe and the laboratory environments. The largest value of shrinkage curvature in the unsealed beam in severe conditions was 1.57×10^{-6} and still increasing. If this is converted to deflection of a 3 m beam, for example, central deflection is calculated to be 1.8 mm, which is unlikely to cause structural problems. No predictions can be made, by extrapolation, of shrinkage response of deep beams, since the details of moisture movements and relative drying are complex and non-linear.

Results of measured creep deformations (excluding shrinkage) deserve detailed consideration with respect to environmental effects, sealing, and whether heat cycling or loading occurred first.

Creep curvatures of unsealed beams under constant moments are plotted in Figure 5, (with compensation for minor differences in applied moment). The beam under daily cycles of air temperature and solar gain (spring conditions) showed rapid early creep, rising to 5×10^{-6} mm^{-1} by about 30 days. The beam under cycles of air temperature only showed slightly less rapid initial creep and a flattening so that creep after 30 days was 4×10^{-6} mm^{-1}. The creep in the beam

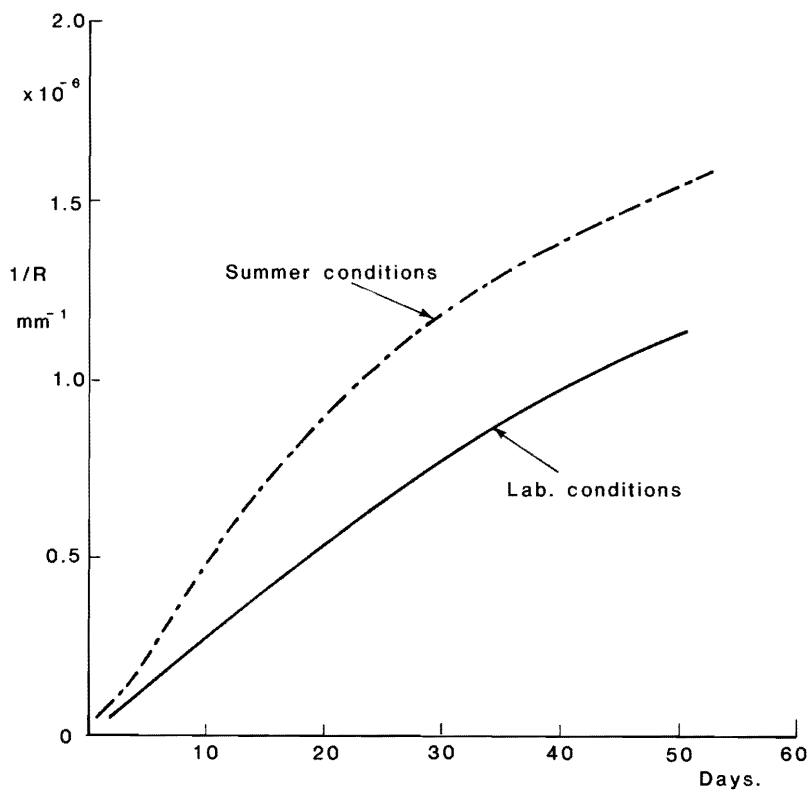

Figure 4. Shrinkage Curvature in Unsealed Beams

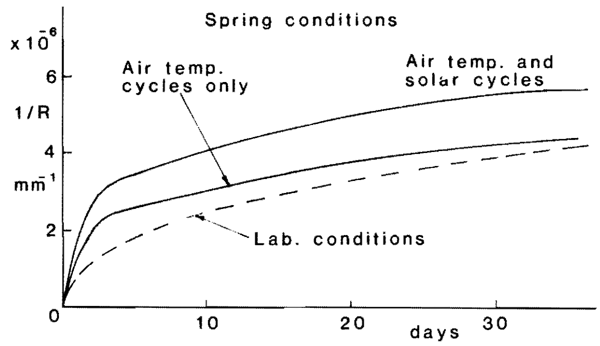

Figure 5. Creep Curvatures of Unsealed Beams

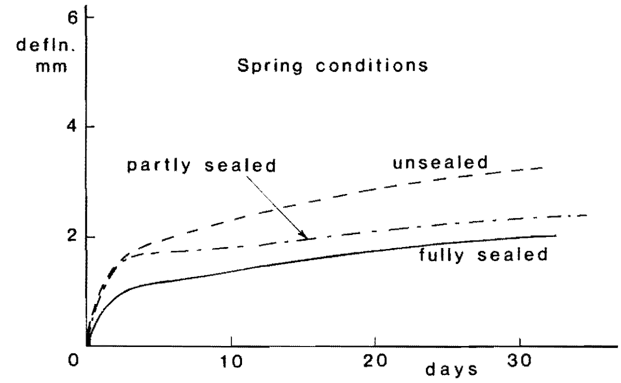

Figure 6. Effects of Sealing on Creep Deflections

under laboratory conditions was much slower at first, but was continuing more rapidly later, so that after 35 days it had nearly caught up with the second curve and was moving closer to the fully-cycled beam. This behavior was caused by near-desiccation of the humidity-cycled beams, which showed rapid early drying creep, but then show less basic creep later. In partly sealed beams which suffered the severe conditions the six day creep curvature was as much as twice that of partly sealed beams in the laboratory, but at later stages creep rate in both sets was about the same. The creep deflections in beams 6II2 and 7I2 were 1.4 mm and 2.4 mm respectively after 32 days. Fully sealed beams showed slight reduction in creep when temperature-cycled due to a small increase in maturity.

In comparing unsealed, partly sealed and fully sealed beams, all exposed to the springtime environment, the fully and partly sealed beams showed similar creep of about 2 mm after 32 days, but in the unsealed beams creep was some 50% greater at 3.2 mm, Figure 6. However, if these creep values were expressed as a factor of elastic deformation, then the three results were all about equal, see Table 4. This demonstrates the beneficial effect of improved curing as a by-product of the sealing condition which limits and delays moisture loss; it is exhibited in reduced immediate deformation and reduced creep. An additional proposition might be derived from these results, that final creep deformation of a singly reinforced beam in conditions of low humidity may be a simple factor of the elastic deformation regardless of sealing conditions; more tests covering variation of additional parameters should be undertaken before such a relation could be defined with confidence.

Unsealed and partly sealed beams showed less creep if they were subjected to two or three diurnal cycles before loading than when loading was applied prior to the cycles. See for example Figure 7. Typically the reduction was of the order of 30%. This can be ascribed to three effects, of increased maturity, reduced gel moisture at time of loading, and to transitional thermal creep [10], which is characterised by the step in the curve at day 4.

Prediction of elastic deformations according to the CP110, CEB-FIP and ACI codes of practice was adequate, see for example Table 5. However, creep deflections were generally under-estimated by the effective modulus approach of CP110 and the CEB-FIP, while the reduction factor method of ACI 209 tended to show slight over-estimates.

Estimation of creep curvature by the specific thermal creep step-by-step approach based upon measured uniaxial creep data was generally satisfactory, see for example Figure 8. However, caution is expressed with

Table 4. Deflections of Unsealed, Partly Sealed and Sealed Beams

	Unsealed beam	Partly sealed	Totally sealed
Elastic deflection	5.82 mm	3.86 mm	3.69 mm
Creep, 0–6 day	2.11 mm	1.71 mm	1.28 mm
6–32 day	1.38 mm	0.65 mm	0.97 mm
0–32 day	3.49 mm	2.35 mm	2.24 mm
32 day creep/elastic	0.60	0.61	0.61
6 day creep/32 day	0.60	0.72	0.57

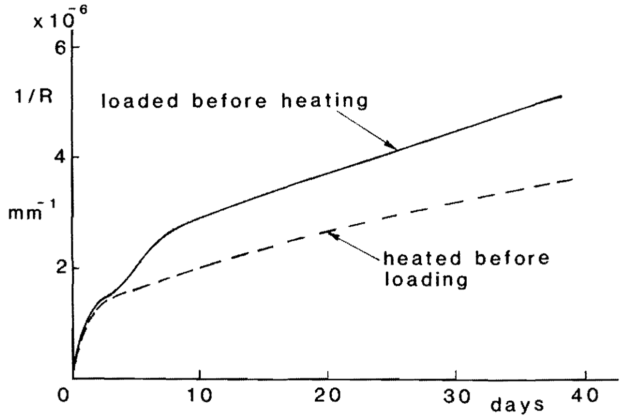

Figure 7. Creep: Diurnal Cycles Before or After Loading

Table 5. Tests and Code Predictions

Beam	Code	Midspan deflection (mm) On loading	Creep
5.III.2	CP110	4.89	1.42
Unsealed,	ACI-435	4.98	3.65
summer	CEB-FIP	4.78	1.55
conditions	Test	3.86	2.43
6.II.4	CP110	4.89	1.42
Partly	ACI-435	5.82	3.82
sealed,	CEP-FIP	4.82	2.29
spring	Test	4.98	4.52
conditions			

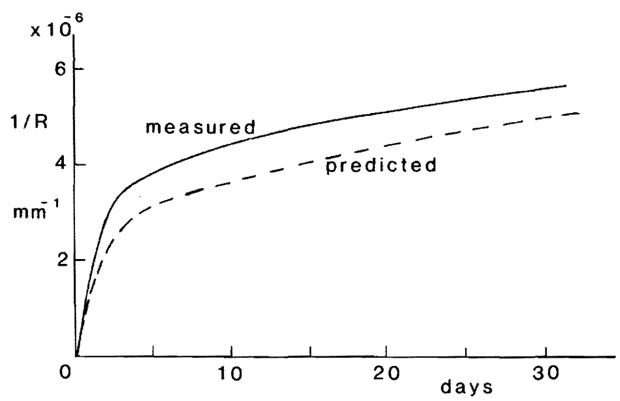

Figure 8. Measured and Predicted Creep Curvature

respect to the major difficulty of maintaining similar moisture conditions in uniaxial and beam specimens, which is critical to reliable prediction.

The experimental results clearly showed that the assumption that creep increases with temperature at all times is incorrect (Figure 5). In an atmosphere of low humidity, the loss of gel water is the dominant factor in both creep and shrinkage.

Finally, a smaller number of tests was undertaken on prestressed beams, 2800 × 200 × 100 mm and prestressed by a central Macalloy bar to around 175 kN, primarily to examine losses in prestress under the severe environment compared with laboratory conditions. Both unsealed and partly sealed beams were tested. Although early age axial creep and shrinkage were accelerated by the diurnal cycling, causing more rapid loss of prestress, the longer term total axial creep and shrinkage was similar in beams which had and had not suffered the extreme environment, (see Figure 9). As in the creep deformation of reinforced beams, the cycling accelerated early age creep and shrinkage but reduced later creep and shrinkage, so that the longer term values were little affected. The measured losses of prestress were of the order of 10% for the partly-sealed beams (regardless of environment), while the prestress losses in the unsealed beams were typically 20%.

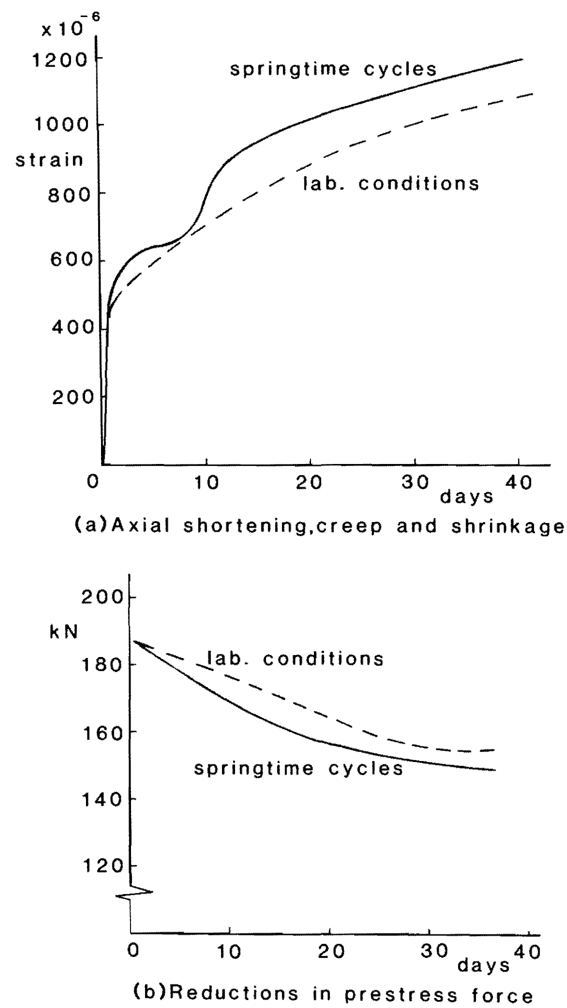

Figure 9. Axial Strains and Prestress Losses in Unsealed Beams

The few sample results, from an extensive test programme, which have been presented are of beams tested in conditions of exposure to the daily cycle of air temperature and of solar radiation, except for one example of a beam in shade air temperatures shown in Figure 5. The general effect of solar radiation, over and above shade air temperatures, is to increase the top concrete surface temperature up to about 63°C (cf. about 45°C), with consequent more rapid creep in the duration of the tests.

CONCLUSIONS

Large temperature differences and high maximum temperatures can be expected in concrete beams and slabs when subjected to air temperatures and solar radiation which occur in climates like that of central Saudi Arabia. The temperature differences have the potential to cause significant stresses in deep concrete members, which should be considered in serviceability design, to avoid excessive cracking.

Results of tests on reinforced concrete beams showed that strain response to the diurnal temperature cycle can be predicted by simple equilibrium methods based on the uncracked concrete section, provided that a realistic estimate of the coefficient of thermal expansion can be made. These cylic movements must be recognized and accommodated in detailed structural design so as to avoid damage resulting from overconstraint, or from cyclic deterioration of a non-compliant bearing.

The creep response of beams under diurnal high temperature/low humidity cycles and varied sealing conditions was complex. The cycling caused very rapid early age creep in unsealed and partly sealed beams, but, because of near desiccation, the later creep in beams in the severe environment was slower than that in beams in laboratory conditions. This contradicts the proposition that heating always increases creep. It was shown that partial or total sealing offered improved curing. It appeared that a simple ratio might exist between final creep and elastic deformations in a particular environment, regardless of sealing conditions. Creep was reduced by imposing the environmental cycling before loading rather than after loading. In summary, creep (and shrinkage) are unlikely to cause unforeseen excessive deflections with consequential serviceability problems, if predictions are made in accordance with the ACI-435 code.

Losses in prestressing forces are accelerated at an early age by the severe climate, but longer term losses are similar to those in beams under laboratory conditions. Therefore, in the beams tested, there was no dangerous loss in prestress, as might have been expected from the proposition of thermal magnification of creep and shrinkage.

The possibility of very rapid carbonation should be investigated under the conditions of elevated surface temperatures as predicted earlier in the paper.

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