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TIME DEPENDENT LOSSES AND DEFORMATIONS OF PRESTRESSED MEMBERS WITH DUE CONSIDERATION OF AGING COEFFICIENT AND PERCENTAGE OF STEEL

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ABSTRACT

Aging coefficient[1,2] which modifies the effective modules for the aging effect is affected by the percentage of steel and its disposition in a member. The value determined by previous workers (i.e. neglecting the effect of reinforcement in the calculation and consequently assuming stiffness coefficient $\alpha = 1$) as bounded between 0.5 and 1 indicates prestress loss less than actual. This difference of prestress loss from the actual one is appreciable for age at loading varying from 180 days to 3 days, with increase in difference of about 8% for lower age at loading of 3 days. If the time of first loading is 28 days and creep coefficient is low, the aging coefficient may be even less than 0.25. The authors have generated additional results as explained in reference (3,4) for age at loading t_o so that 7 days $\leq t_o \leq$ 28 days and found that the aging coefficient is always positive for $\alpha\phi$ (product of stiffness coefficient and creep coefficient) values greater than 0.30, 0.20, 0.10, and 0.075 for values of $t_o \geq$ 7 days, 10 days, 14 days and 28 days respectively.

Deferred initial loading indicates that if the loads are applied at 90 and 180 days, then the losses may be reduced up to 70 and 60 percent respectively.

Total prestress loss reduces for increase in steel ratio. The percentage of loss completed is also greater for higher percentage of reinforcement with optimum value of about 1 percent.

Creep deformation varies directly with the product of the creep coefficient and the creep reduction coefficient. For singly reinforced section, the reduction coefficient generally varies from 1.0 to 0.6. Although the creep reduction coefficient increases for higher grades of concrete, its product with creep coefficient decreases.

It is essential to consider the above aspects in design of reactor vessels where concrete is used to provide the necessary biological shielding and is prestressed from structural design point of view.

Aging coefficient[1,2] modifies the effective modulus for the aging effect. Neglecting the effect of reinforcement and consequently assuming stiffness coefficient[3,4,5] as unity, calculated prestress loss is less than actual. Hence, aging coefficient is calculated to attain an unbounded value of creep strain based on creep functions as per recommendations of ACI Commitee 209 and creep correction factors as per reference 6.

Table 1 shows values of aging coefficients for 27 sets of beam samples(4) for variation of different parameters including percentage of steel, stiffness coefficient, cube crushing strength and creep coefficient. Fig. 1&2 show aging coefficient plotted as a function of age at first loading(t_o) for different values of load duration ($t-t_o$). Fig. 3 shows typical curves for aging coefficient plotted as a function of age at first loading for different values of cube crushing strength (F_{cu}), percentage of steel (p) corresponding to ($t-t_o$) = 10000 days.

Fig. 4 & 5 show aging coefficient plotted as a function of load duration ($t-t_o$) in log scale for different values of $\alpha\emptyset$ i.e, product of stiffness coefficient and creep coefficient for variation of date of loading to.

Fig. 6 shows typical curves for stress relaxation ratios(4) plotted as a function of load duration ($t-t_o$) in log scale of different samples for variation of F_{cu}, p and t_o.

Formulation of the method, determination of loss of prestress, creep curvature reduction coefficients, shrinkage curvature reduction coefficients and recovery factors are explained in reference 2 and 4.

Effect of deferred initial loading and percentage of steel on losses and deformations are explained in reference 4.

CONCLUSIONS

1. Aging coefficient is not the same for plain concrete and reinforced/ prestressed concrete. It is affected by the percentage of steel and its disposition in a member. Values of aging coefficients calculated previously by Neville(5) are considerably higher than they are in actuality, making the prediction of prestress loss less, particularly for early loading ages.

   However, a detail analysis (computer based parametric study using a step-by-step approach) has been made in reference 4 for accurately determining the aging coefficient with due consideration for disposition

Aging coefficient as a function of the age at first loading for different values of $\alpha\emptyset$ or F_{cu}, p corresponding to load duration $(t-t_o)$.

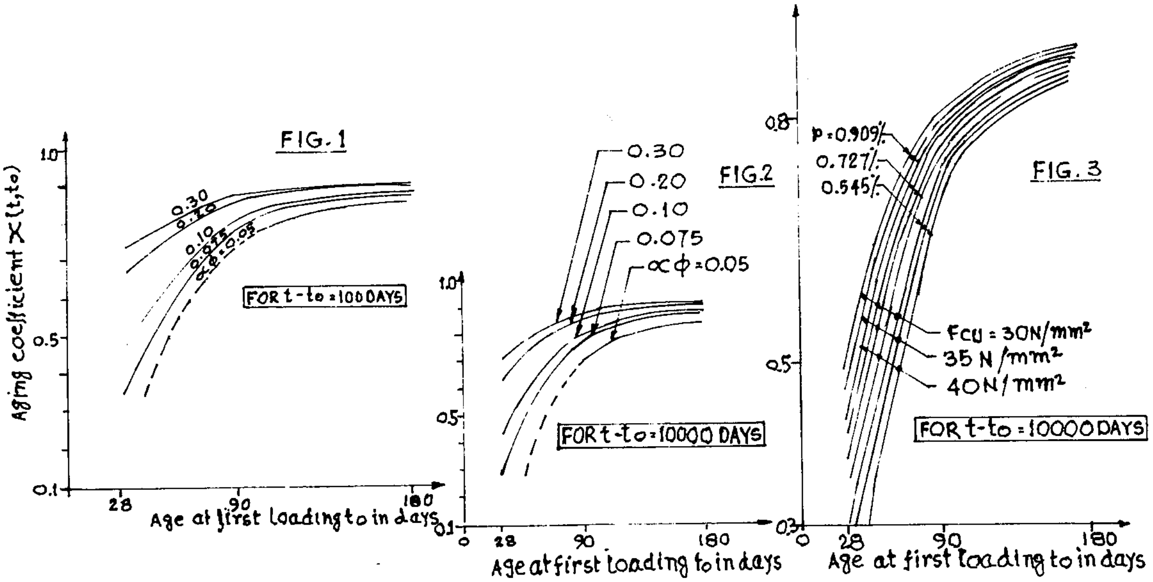


TABLE - 1

Sample number	Cube Crushing Strength Fcu N/mm²	Age at Loading to days	Reinforcement percent p	Stiffness Coefficient ∝C	Creep Coefficient $\phi(t,t_o)$ After 1000 days of loading	Creep Coefficient $\phi(t,t_o)$ After 10000 days of loading	Aging Coefficient $\chi(t,t_o)$ After 1000 days since loading	Aging Coefficient $\chi(t,t_o)$ After 10000 days since loading	* Total Loss in steel stress after 10000 days N/mm²	After (t − t_o) = 365 days: Shrinkage curvature reduction coefficient	After (t − t_o) = 365 days: Creep Curvature reduction coefficient	After (t − t_o) = 365 days: Curvature × 10^6 cm^{-1}	After (t − t_o) = 365 days: Deflection mm × 10^2
1	30	28	0.545	0.0535	1.259	1.404	0.291	0.275	142.64	0.091	0.856	42.95	31.28
2	"	"	0.727	0.0701	"	"	0.427	0.410	80.20	0.124	0.803	42.97	32.07
3	"	"	0.909	0.0861	"	"	0.509	0.492	66.69	0.152	0.759	43.53	33.44
4	"	90	0.545	0.0509	1.096	1.222	0.767	0.741	112.96	0.113	0.819	37.96	26.89
5	"	"	0.727	0.0668	"	"	0.805	0.782	54.62	0.142	0.774	37.97	27.47
6	"	"	0.909	0.0821	"	"	0.828	0.807	52.08	0.166	0.735	38.23	28.34
7	"	180	0.545	0.0503	1.100	1.128	0·881	0.861	98.91	0.114	0.817	35.64	24.75
8	"	"	0.727	0.0660	"	"	0.896	0.879	45.04	0.142	0.772	35.71	25.36
9	"	"	0.909	0.0812	"	"	0.906	0.890	42.84	0.166	0.734	35.98	26.17
10	35	28	0.545	0.0497	1.216	1.355	0.247	0.231	141.64	0.084	0.875	39.55	28.77
11	"	"	0.727	0.0652	"	"	0.394	0.377	78.33	0.116	0.828	39.60	29.45
12	"	"	0.909	0.0802	"	"	0.482	0.465	74.93	0.144	0.786	40.17	30.75
13	"	90	0.545	0.0473	1.059	1.180	0.755	0.729	111.51	0.107	0.840	34.80	24.52
14	"	"	0.727	0.0621	"	"	0.796	0.772	52.50	0.135	0.797	34.86	25.07
15	"	"	0.909	0.0764	"	"	0.820	0.799	50.03	0.160	0.760	35.16	25.92
16	"	180	0.545	0.0467	0.976	1.088	0.876	0.855	97.30	0.109	0.837	32.74	22.67
17	"	"	0.727	0.0613	"	"	0.893	0.875	42.88	0.136	0.796	32.80	23.15
18	"	"	0.909	0.0755	"	"	0.903	0.887	40.74	0.161	0.760	33.05	23.89
19	40	28	0.545	0.0466	1.174	1.308	0.183	0.167	141.11	0.075	0.892	36.43	26.33
20	"	"	0.727	0.0612	"	"	0.345	0.329	76.78	0.107	0.850	36.59	27.01
21	"	"	0.909	0.0754	"	"	0.443	0.426	74.15	0.135	0.811	37.17	28.28
22	"	90	0.545	0.0444	1.023	1.140	0.738	0.710	110.48	0.100	0.858	32.34	22.74
23	"	"	0.727	0.0583	"	"	0.782	0.758	50.66	0.128	0.819	32.40	23.20
24	"	"	0.909	0.0718	"	"	0.810	0.787	48.88	0.153	0.784	32.62	23.89
25	"	180	0.545	0.0438	0.943	1.050	0.868	0.847	96.06	0.103	0.855	30.32	20.88
26	"	"	0.727	0.0576	"	"	0.887	0.868	40.93	0.129	0.817	30.40	21.33
27	"	"	0.909	0.0710	"	"	0.898	0.881	39.44	0.153	0.783	30.62	21.98

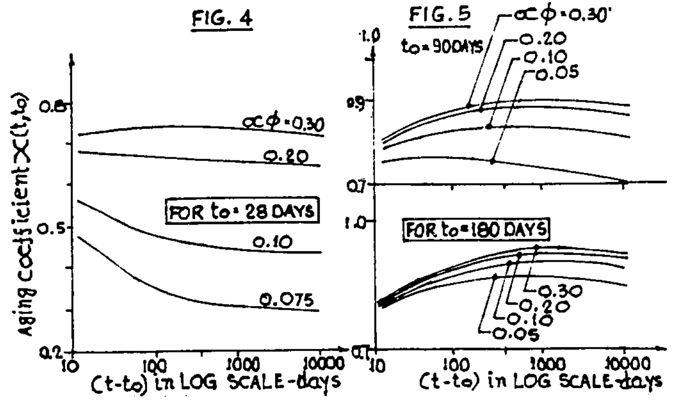
* Total Loss (for prestress plus dead load plus live load condition) for concrete stress in c.g. of steel at transfer equal to 8.7 N/mm² and equal to 3.56 N/mm² including effect of live load.

NOTE : 1. Shrinkage and creep curvature reduction coefficients are as per reference 2 & 4.

2. Curvature & deflections are at the centre of 1 metre span beams, subjected to a total force P=59870 Newtons at transfer. Live load bending moment at mid span equal to 3530 N.m.

Aging coefficient as a function of time under load for various values of $\alpha\emptyset$ corresponding to age at loading t_o.

FIG. 4 FIG. 5



and percentage of prestressing steel, creep coefficient, concrete aging & variation of modulus of elasticity of concrete with time.

From the results obtained it is observed that keeping all other parameters unchanged the aging coefficient $x(t,t_o)$ decreases for all factors that lead to the decrease of $\emptyset$ or $\alpha\emptyset$. Effect of different parameters on aging coefficient is explained in reference 1 & 4.

Table 1 & Fig. 1 and 2 show that keeping age at first loading (t_o) unchanged, corresponding to any two $\alpha\emptyset$ values, the difference in aging coefficients increases with increased duration of loading. Fig. 4 & 5 show Aging Coefficients plotted as a function of time under load for various values of $\alpha\emptyset$ and confirm convergence of aging coefficients with later date of loading (t_o = 180 days) even for a wide variation (from 0.05 to 0.30) of $\alpha\emptyset$ value.

Thus, for early date of loading (to $\leqslant$ 28 days) and longer duration of time $(t-t_o) \geqslant$ 1000 days, predicted aging coefficient will differ widely from its actual value unless effect of reinforcement and stiffness coefficient are taken into consideration.

In Table 1 it has been established that contrary to Neville$^{(5)}$ and general conception, the value of the aging coefficient is not necessarily bounded between 0.5 and 1.0. If the time of first loading is less (say 3 to 28 days, which is reasonable in most of the practical cases) and creep coefficient $\emptyset(t,t_o)$ is low, the value of the aging coefficient may be less than 0.2 but gives positive value for all practical cases.

Aging coefficients of the samples plotted as a function of the age at first loading for different values of cube crushing strength (F_{cu}) and percentage of reinforcement (p) for load duration = $(t-t_o)$ = 10,000 days are shown in Fig. 3. This shows that for any particular date of loading (t_o) and upto any duration of load $(t-t_o)$, the aging coefficient is maximum for sections with maximum percentage of steel and minimum cube crushing strength. Similarly, keeping all other parameters unchanged the aging coefficient is minimum for sections with maximum cube crushing strength and minimum percentage of steel.

Hence, for a particular characteristic strength of concrete, an optimum percentage of steel may be chosen to predict minimum loss (of prestress due to creep) and vice versa.

Fig. 4 and 5 show that for early date of loading ($t_o \leqslant$ 28 days), all curves are concave in nature and value of the aging coefficient reduces for increase in load duration. But, for later date of loading ($t_o >$ 28 days), curves are convex upward showing that the aging coefficient increases upto about $(t-t_o)$ = 365 days, beyond which the value decreases.

Stress relaxation ratio of different samples as a function of time under load.

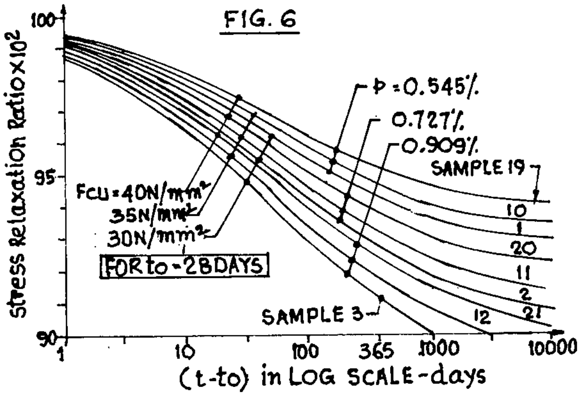


FIG. 6

These also depict convergence of curves for smaller duration (t-t_o). From the above, contrary to Neville's (5) observation it is established that the aging coefficient is also dependent on the time elapsed since application of the load and hence should be considered in calculation.

Unlike Neville's(5) and general conception, in Fig. 1 through 3 it is shown that the aging coefficient is not linearly dependent with age at first loading (t_o). In actuality, the increase is sharp upto t_o = 90 days, beyond which slope of the curve diminishes and becomes asymptotic after t_o = 180 days.

2. Introducing unit strain at the time of loading (t_o) and using the step-by-step approach, for t_o = 28 days the stress at the end of interval (t_n-t_o) = 1, 10, 100, 365, 10000 are represented in Fig. 6. This reveals that keeping all other parameters unchanged the relaxation function, as well as the ratio of final stress to the initial stress due to unit strain imposed at the time of loading t_o(generally called a stress - relaxation ratio) reduces with an increase in the percentage of steel. The study further revealed that predicted stress relaxation ratio is too low for ignoring effect of steel in reinforced/prestressed concrete i,e. depending on stiffness coefficient, stress relaxation ratio is higher compared to plain concrete samples. Ignoring stiffness coefficient, relaxation function calculated is less making the prediction of prestress loss lower than in actuality. The study confirms that stress relaxation ratio decreases for all factors that increase the value of creep coefficient or its product with corresponding stiffness coefficient. Also, the relaxation function and stress relaxation ratio increases and corresponding prestress loss decreases when age at loading (t_o) is increased.

   Fig. 6 shows that for any particular date of loading and upto any duration of load, stress relaxation ratio is maximum for sections with minimum percentage of steel and maximum characteristic strength.

   Since stress relaxation ratio decreases for any increase in the aging coefficient, it also allows to predict loss of prestress due to creep corresponding to any set of values for f_{cu}, p and t_o.

3. Creep coefficient (defined as the ratio of creep to elastic strain) of three different grades of concrete viz. M-30, M-35 and M-40 corresponding to samples 1 through 9, 10 through 18, & 19 through 27 respectively shows that it increases when : (i) grade (strength) of concrete used is decreased, (ii) age at loading is decreased and (iii) duration of applied load is increased.

   Creep curves for (prestress + dead load) and (prestress + dead load + live load) conditions are similar in nature. The curves show that upto a period of one month, slope increases sharply followed by a period when creep increases at a constant rate. Beyond this period the slope of creep curve diminishes but does not become asymptotic within the time range (of $t-t_o$ = 10000 days) studied.

Loss of prestress of different samples due to creep when plotted as a function of time under load for t_o = 28, 90, 180 days and p = 0.545%, 0.727%, 0.909% show minimum value for later date of loading in combination with maximum percentage of steel and vice versa.

This confirms importance of steel percentage in reducing loss of prestress due to creep.

4. From Table 1 the effect of deferred initial loading can be predicted, comparing total losses at different intervals of time $(t_n - t_o)$ to the total losses occuring after 10000 days of loading assuming negligible increase in loss beyond 10000 days. This comparison indicates that, if the loads are not applied at 28 days but deferred to 90 and 180 days, then the losses are reduced to 70-75% and 60-65% respectively.

   It is felt that the above information is useful particularly for members where full live load is not active from the date of release of wires.

   Total prestress loss of different samples exhibit that prestress loss reduces appreciably for slight increase in steel percentage (p). With later age at loading (t_o) and higher grade of concrete (F_{cu}) the prestress loss reduces further.

   Keeping the date of loading and period under load unchanged, for steel percentage p = 0.545, 0.727, 0.909 the percentage of loss completed at time $(t - t_o)$ = 100 days are 55%, 72% and 77% respectively. The corresponding percentage of loss completed at time $(t-t_o)$ = 1000 days are 80%, 91%, 94%.

   Hence, deferred initial loading & increase in steel ratio reduces prestress loss appreciably. For lower percentage of steel, total prestress loss increases significantly beyond several decades but for higher percentage of steel, total prestress loss depicts an asymptotic nature.

5. Introduction of creep curvature reduction coefficient $\theta_{cr(t)} < 1.0$ as per reference 2 & 4 permits to assume that creep curvature of a reinforced/prestressed concrete section is less than plain concrete section due to the presence of reinforcement. From a study of 27 beam samples, it is seen that for a singly reinforced member, the creep reduction coefficient generally varies from 1.0 to 0.6. Keeping all other parameters unchanged, the creep reduction coefficient (θ_{cr}) of singly reinforced section reduces for the following cases :

   (i) Higher the ratio of Y_{CGS}/r; (ii) Higher the value of (p); (iii) Later the age at loading (t_o); (iv) Lower the grade of concrete used.

6. The effect of warping is accounted for by using shrinkage reduction coefficient (θ_{sh}) as per reference 2 & 4 and furnished in Table 1. Total time dependent effect is greatly influenced by shrinkage (for ultimate shrinkage strain $S_\infty > 600 \times 10^{-6}$). In such cases, similar to shrinkage effects, total time dependent deflection of singly reinforced members (subjected to prestress + dead load + live load) may increase for increase in percentage of steel, but decreases for deferred date of loading and increased strength of concrete.

7. As per Neville(5), creep is partly irreversible due to non linear effect and recovery of specimens unloaded are less than that calculated based on principles of superposition.

   Utilising this concept, measured deformations show that deviations are less than 10 percent of the calculated theoretical values.

NOTATION

F_{cu} = Cube crushing strength
n = Modular ratio
p = Steel area ratio
r = Radius of gyration
S_{α} = Ultimate shrinkage strain
t_o = Time of loading
$(t-t_o)$ = Load duration
$X(t,t_o)$ = Aging coefficient at time t for load applied at time t_o

$$= \left(1 - \frac{\sigma_t}{\sigma_c}\right)^{-1} - \frac{1}{\alpha\, \phi(t,t_o)}$$

Y_{CGS} = Eccentricity of centre of gravity of steel

α = Stiffness coefficient = $\dfrac{pn(1 + Y_{CGS}^2/r^2)}{1 + pn(1 + Y_{CGS}2/r^2)}$ for an eccentrically reinforced/prestressed member.

$\phi(t,t_o)$ = Creep coefficient at time t for constant stress acting since time t_o

σ_c = Normal initial stress, i,e stress at the time of loading

σ_t = Normal stress at time t

θ_{cr} = Creep curvature reduction coefficient

θ_{sh} = Shrinkage curvature reduction coefficient

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