EVALUATION OF MATERIAL MODELS FOR SHRINKAGE AND CREEP OF CONCRETE

Dr.ing. Terje Kanstad
Division of Concrete Structures
The Norwegian Institute of Technology
The University of Trondheim, Norway

Abstract: Creep and shrinkage results were obtained in this study and used to evaluate two material models, the Bazant-Panula model and the model presented in the CEB 1990 Model Code. The effects of material composition and environmental conditions were studied in particular.

Key-words: Concrete, material models, timedependence, creep, shrinkage, material composition, environmental conditions.

1.Introduction

In an investigation entitled "Nonlinear Analysis Considering Timedependent Deformations and Capacity of Reinforced and Prestressed Concrete" /1/, various material models for predicting the short- and longterm behaviour of concrete were studied. The research project was motivated by a general interest in the subject of timedependent behaviour of concrete structures and the need for more accurate design methods. A finite element program was developed for the analysis of planar reinforced and prestressed concrete frames. Both material and geometric nonlinearities were accounted for and the time dependent effects due to load history, creep and shrinkage of concrete and relaxation of prestressing steel were considered. The principle of superposition of strains was assumed for the longtime analysis. Numerical studies of concrete structures were also carried out. The analyses include short- and longterm studies of reinforced and prestressed beams and slender columns. Comparisons to experimental results were performed. In this paper only longterm material models in comparison with results on creep and shrinkage specimens are considered.

The theoretical background for the material models and hypotheses for the physical explanations of creep and shrinkage are described in the literature /1,3,5/. These subjects are important for the understanding of the material models if reasonable improvements should be suggested. When the creep and shrinkage model in the CEB 1990 Model Code proposal (MC 90) /2/ was published in 1988, it seemed interesting to carry out a comparison between this model and the Bazant-Panula-model (BP-model) /3/. This interest was partly due to the fact that the BP-model so far was believed to be the most accurate model presented in the literature. It was interesting to note that the models are quite different in the way they consider the effect of concrete composition. While the BP-model uses the compressive strength and the relative weigths of water, cement, and fine and coarse aggregate as the main material parameters, the MC 90 model uses only the compressive strength and the cement type as material parameters. Below follows a short presentation of the material models, with comments to some of their main features, and comparisons with experimental results.

2.The Bazant-Panula Model

The complete description of this model is given by Bazant and Panula in three papers, published in Materials and Structures (RILEM) in 1978-79 /3/. Only some basic features, needed in the subsequent comparison and evaluation of the models, are reviewed. The compliance function, which expresses total stress-dependent strain per unit stress, is written as:

$$J(t,t',t_o) = 1/E_o + C_o(t,t') + C_d(t,t',t_o) - C_p(t,t',t_o) \qquad (1)$$

The total stress dependent strain is given as:

$$\epsilon(t) = J(t,t',t_o)\cdot(t') \qquad (2)$$

In these equations t (in days) is the current time, t' the concrete age at loading, while t_o is the concrete age when drying starts. The total stress dependent strain is assumed to consist of an instantaneous part ($1/E_o$) and a basic creep term ($C_o(t,t')$), which gives the total deformation of a specimen never exposed to drying (sealed or stored wet). Further there are the drying creep terms, which are due to an increase in strain because of simultaneous drying ($C_d(t,t',t_o)$) and a reduction in strain due to predrying ($C_p(t,t',t_o)$). The formulas for each term are quite comprehensive and are not reviewed here. They were developed by means of optimization techniques used to minimize the deviations from a large amount of experimental data available in the literature.

The model is "semi-empirical" in the sense that it has features related to diffusion theory for humidity effects and activation energy theory for thermal effects. For shrinkage the time function is given as $S(t-t_0)=\sqrt{(t-t_0)/(\tau_{sh}+(t-t_0))}$. The term τ_{sh} is proportional to the square of the volume/surface-ratio (effective cross section thickness) and inversely proportional to an estimate for the concrete's diffusivity. Time functions for shrinkage are shown in Fig.1 for cylinders and prisms of different dimensions. Fig.2 shows the effect of predrying (drying before the load is applied) on the drying creep term for cross sections of different dimensions at different temperatures. A similar effect is included for basic creep through the term $C_p(t,t',t_o)$.

The model is applicable for temperatures in the range between 20 and 70°C. At elevated temperatures, the basic creep is given a relatively large increase through a scaling factor in addition to a faster development in time, while the drying creep term is not increased with the temperature. As seen in Fig.2, the effect of predrying increases at elevated temperatures.

The BP-model has quite comprehensive equations describing the effect of compressive strength and material composition. The water/cement-, the aggregate/cement-, and the gravel/sand-ratio are significant material parameters in this model.

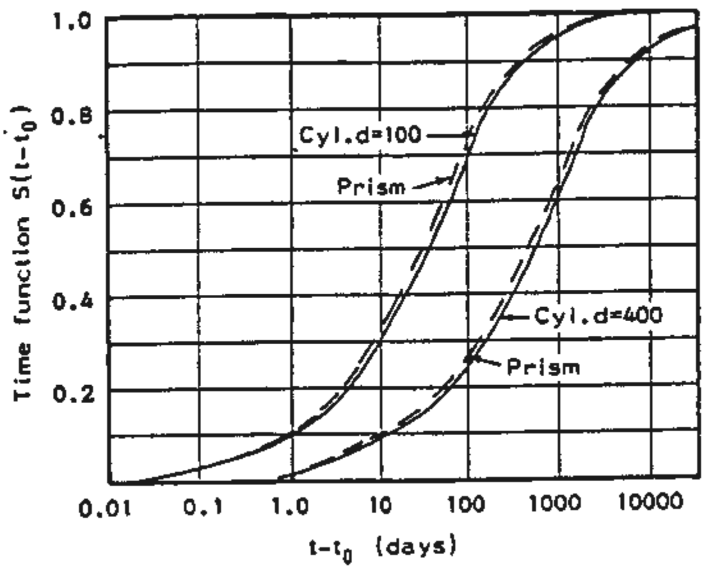

Figure 1. Time functions for shrinkage in the BP-model, cylinders and prisms of different dimensions.

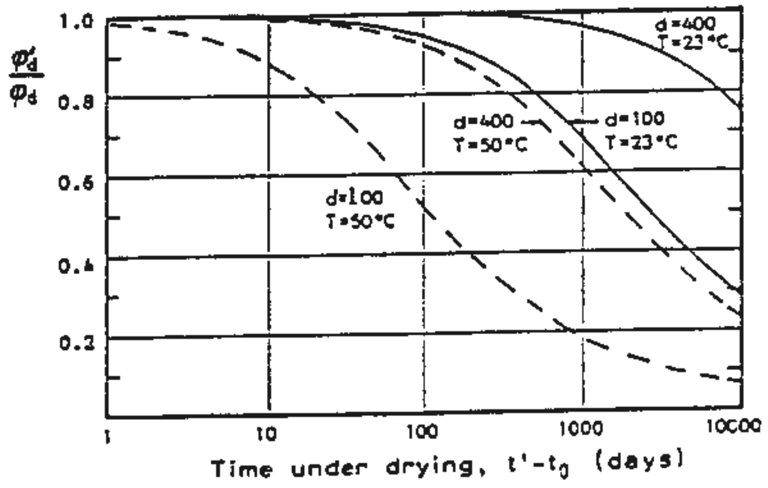

Figure 2. Effect of predrying time on the drying creep term in the BP-model.

3.The MC 90 Model

While the creep model in the previous Model Code (1978) was related to the "rate of flow method" /4/, the model in the new Model Code (MC 90) is related to the principle of linear superposition of strains. Further the new model has similarities to the Bazant-Panula model in the way it considers the effects of drying and cross section size. The equations considered in the present work were published in the Model Code Proposal of September 1988 /2/. Later the model has been slightly modified and is more completely described in the CEB-Bulletin "Evaluation of the Time Dependent Behavior of Concrete" /5/. These modifications, however, are not important in the following discussion. The compliance function may be written as:

$$J(t,t') = \frac{1}{E_c(t')} + \frac{\varphi(t,t')}{E_c(t'=28d)} \tag{3}$$

In which the creep ratio $\phi(t,t')$ is given as:

$$\varphi(t,t') = \varphi_{RH} \cdot \beta(f_{cm}) \cdot \beta(t') \cdot \beta(t,t') \tag{4}$$

The influence of the relative humidity of the ambient air is accounted for by the term ϕ_{RH} which increases with decreasing relative humidity. The term is also increasing with decreasing volume/surface-ratio (D=2V/S), and is illustrated in Fig.3a for cylinders of different diameters at different temperatures. When elevated temperatures are considered, it is interesting to note, that creep is largest when simultaneous drying takes place, which is in disagreement with the BP-model. Further there is no effect of predrying in MC 90, even at elevated temperatures. By means of the coefficients $\beta(f_{cm})$ and $\beta(t')$, which both are hyperbolic functions, the creep coefficient is decreasing with increasing compressive strength (f_{cm}) and increasing age at loading (t'). The time function, $\beta(t,t')$, is given as:

$$\beta(t,t') = \left(\frac{t-t'}{\beta_H + (t-t')}\right)^{0.3} \tag{5}$$

$$\beta_H = 1.5\,(1 + 0.00012(RH/50)^{18})\,D + 250 \leq 1500 \text{ mm} \tag{6}$$

In this model the time functions are equal in non-dimensional time given as $(t-t')/\beta_H$. Both drying and decreasing specimen size will accelerate the creep strain. Typical time functions are shown in Fig.3b. A similar time function is also used for shrinkage.

The compressive strength and the cement type are the only material parameters used, and both the creep ratio and the final shrinkage strain are decreasing with the strength. According to this model, the cement type is an important parameter for shrinkage, and the high strength rapid hardening cements will give the largest shrinkage strains.

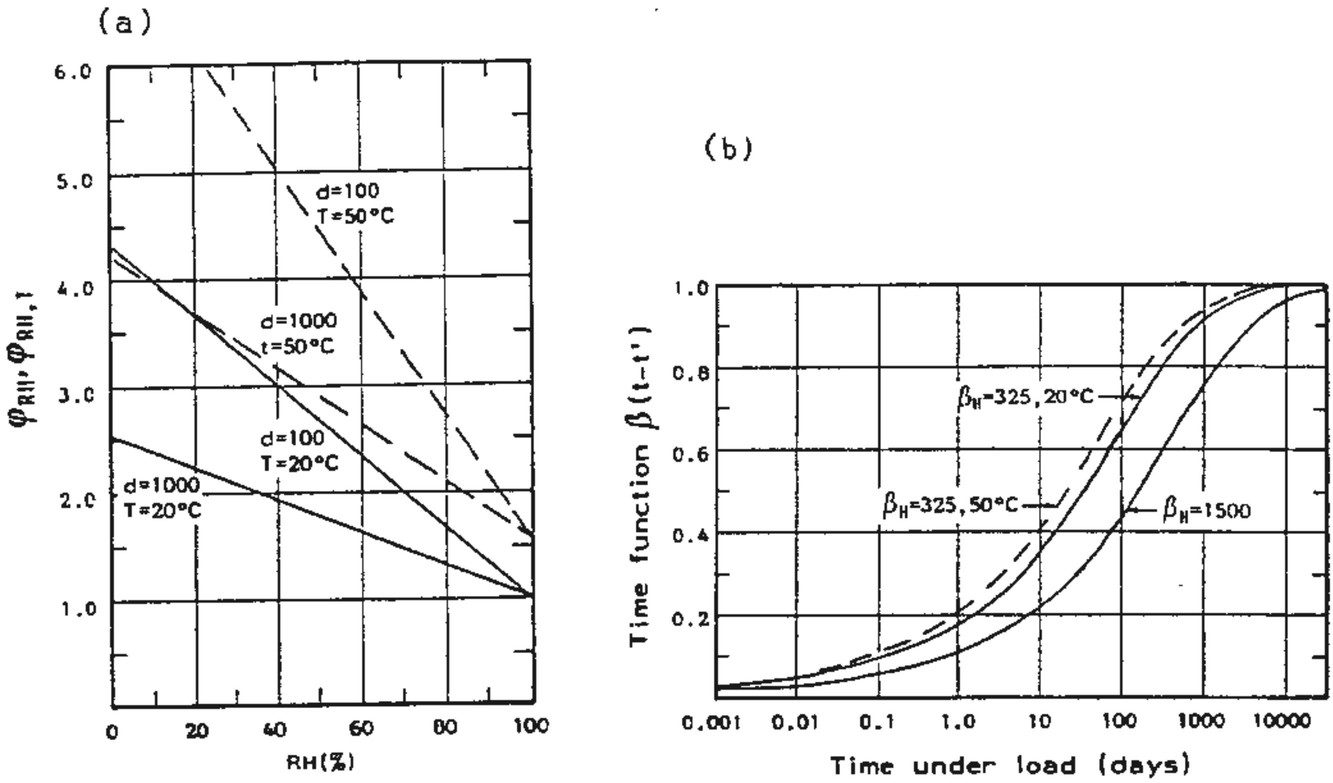

Figure 3. (a) Influence of the relative humidity and the temperature on the creep coefficient in MC 90. (b). Time functions for creep for minimum and maximum values of the β_H-parameter.

4.Comparison with Experimental Results

Effects of material composition, size and shape of specimen, and temperature and relative humidity of the ambient air, were studied previously by the author /1/. Although, the main purpose was to carry out an evaluation of the material models, the intention was also to contribute to a better understanding of the reasons for the large scatter in experimental observations on creep and shrinkage. It should be noted that these comparisons were not carried out in a statistical sense, but merely in a way trying to evaluate the models to experimental series where only a few parameters were varied. In this way, the present investigation is different from the original presentations of the models.

4.1 Shrinkage

Considering the effect of material composition, a reduced w/c-ratio and a corresponding increased strength might implicate reduced shrinkage. As shown in Fig.4, where shrinkage strains versus cement content are shown for three experimental series, this is dependent on the particular concrete composition. The figures also give an idea about the accuracy of the models. It is seen that the MC 90 model's general reduction in shrinkage with strength at least is questionable.

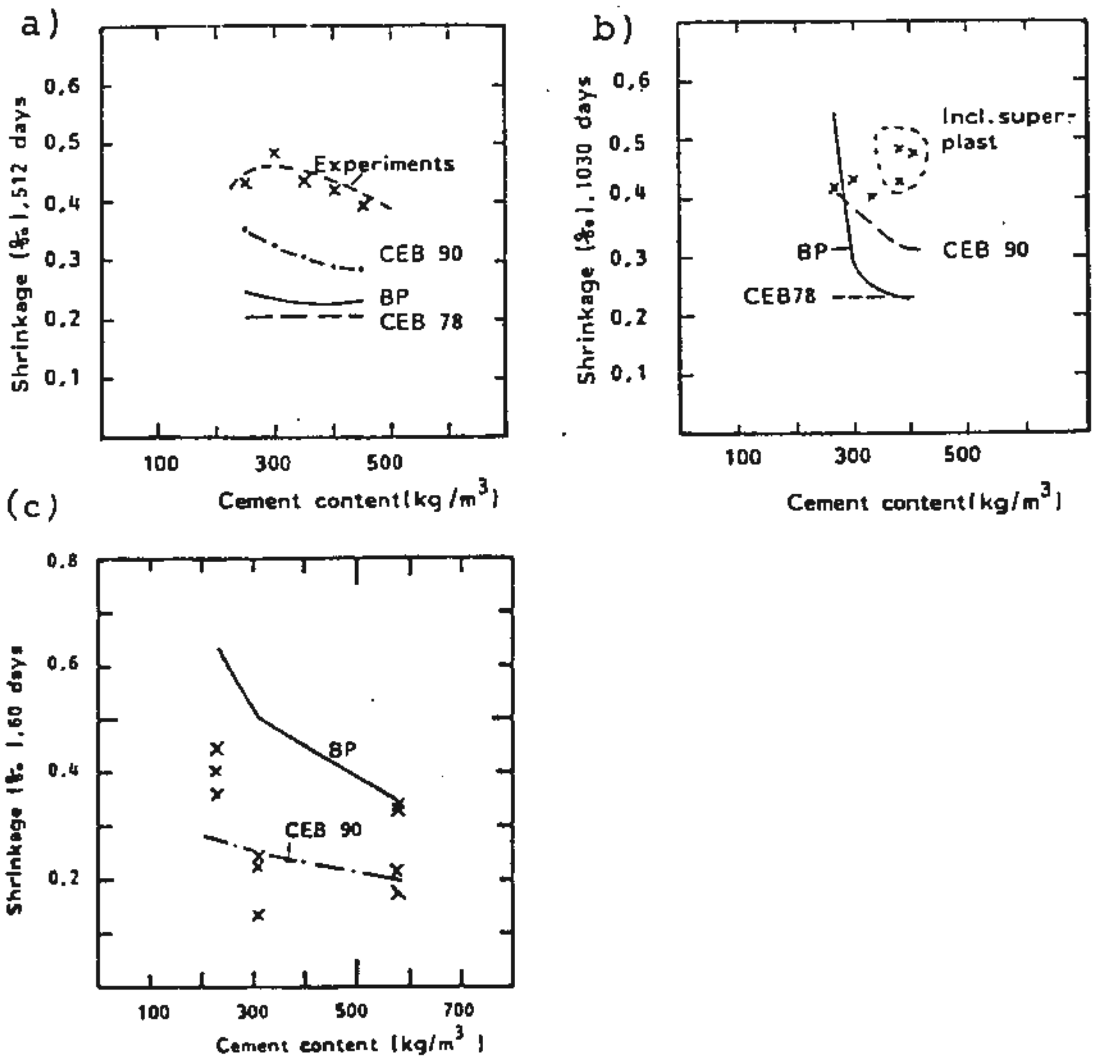

	Figure a)				
Cement (kg/m³)	250	300	350	400	450
w/c-ratio	0.63	0.54	0.45	0.41	0.36
Aggregate/cement	8.21	6.62	5.50	4.64	4.01
Superplast. (%)					
28 d cyl. strength	33.0	41.5	47.6	54.2	56.5

	Figure b)						Figure c)		
Cement (kg/m³)	266	296	332	379	378	404	229	310	581
w/c-ratio	0.65	0.55	0.45	0.37	0.35	0.34	0.87	0.65	0.32
Aggregate/cement	7.37	6.59	5.84	5.09	5.11	4.72	8.60	6.10	2.81
Superplast. (%)				1.0	2.0	2.0			yes
28 d cyl. strength	26.0	36.6	46.1	52.3	56.9	56.9	23.1	37.7	61.9

Figure 4. Shrinkage versus cement content. (a) Experimental results of Alou et.al., constant water content, (b) Alou et.al. constant cement paste volume, (c) Smadi et.al., typical low, medium and high strength concretes /1/.

The type of cement has a large influence on shrinkage as seen in Fig.5. This might be due to the effect of hydration rate, because the unhydrated cement grains might act as a part of the restraining volume of the aggregates. The BP-model does not seem to predict well the effect of cement type on shrinkage, because this model gives a relatively large reduction of shrinkage with increasing strength. The effect is better predicted by the MC 90 equation since a particular parameter is included to account for the increased shrinkage observed when rapid or high strength cements are used.

By comparisons to several experimental series, the author has shown /1/ that the effect of the gravel/sand-ratio is overestimated in the BP-model. This is the reason why this model sometimes gives relatively poor agreement with experimental behaviour.

In both the BP-model and the MC 90 model, the size effect on shrinkage is in accordance with diffusion theory. It is shown that this is in reasonable agreement with experimental behaviour /1/. In the BP-model, the influence of material composition on the time function is accounted for by a formula in which the diffusivity is linearly increasing with the water content. This leads to relatively slower shrinkage development in concretes with lower water content, which is not in agreement with experimental observations. In both models the relative humidity of the ambient air is accounted for by the multiplication factor 1-$(RH/100)^3$. Considering elevated temperatures the development of shrinkage is accelerated in both models. The influence of temperature on the final shrinkage is small in both models.

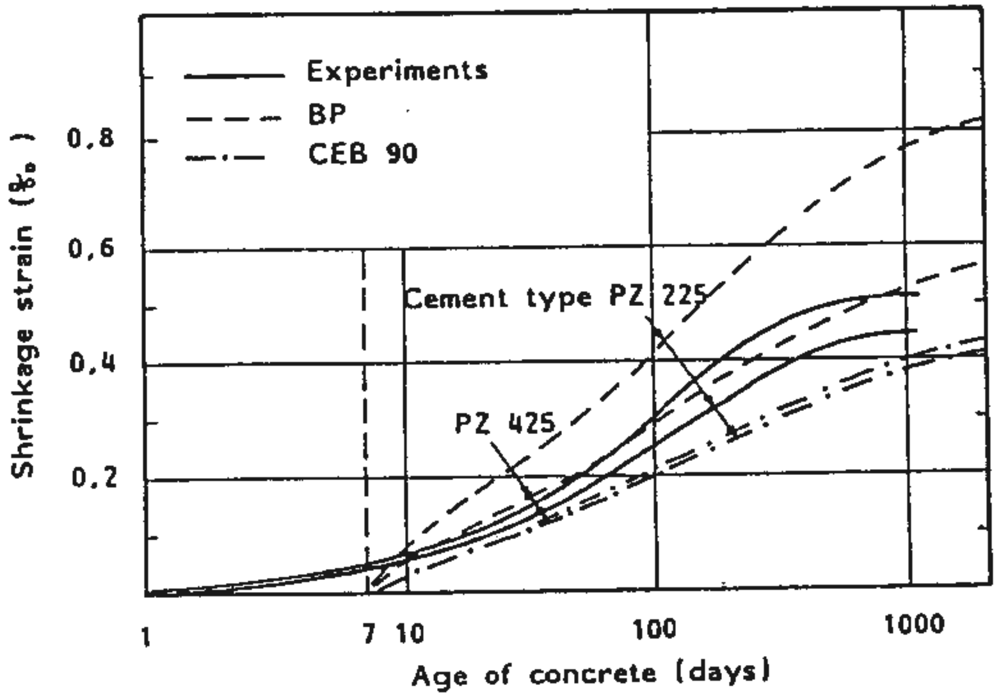

Figure 5. Shrinkage development for concretes of different cement types, Hummel et.al. /1/. PZ 225 Normal cement, PZ 425 High strength cement

4.2. Stress dependent deformations

The creep deformation is generally increasing with w/c-ratio, even though the aggregate/cement-ratio is increasing. Considering a two-phase model this means that the properties of the different phases are more significant than their relative volumes. It is shown in /1/ that the increase in deformations with the w/c-ratio is more pronounced for longtime than for shorttime behaviour. The effect of cement type on creep is large and seems also to be more pronounced for creep than for shorttime deformations.

The effect of material composition in the BP-model is not in general agreement with experimental observations. For instance, the relatively strong influence of strength on both basic and drying creep in this model resulted in confusing results for the effect of cement type and w/c-ratio. This is demonstrated in comparisons with experimental series where only the w/c-ratio (Fig.6a) or the cement type (Fig.7a), is varied. In MC 90, the ratio between creep and instantaneous deformations is reduced with increasing strength. This is reasonable for normal strength concretes studied in this work (Fig.6b and 7b).

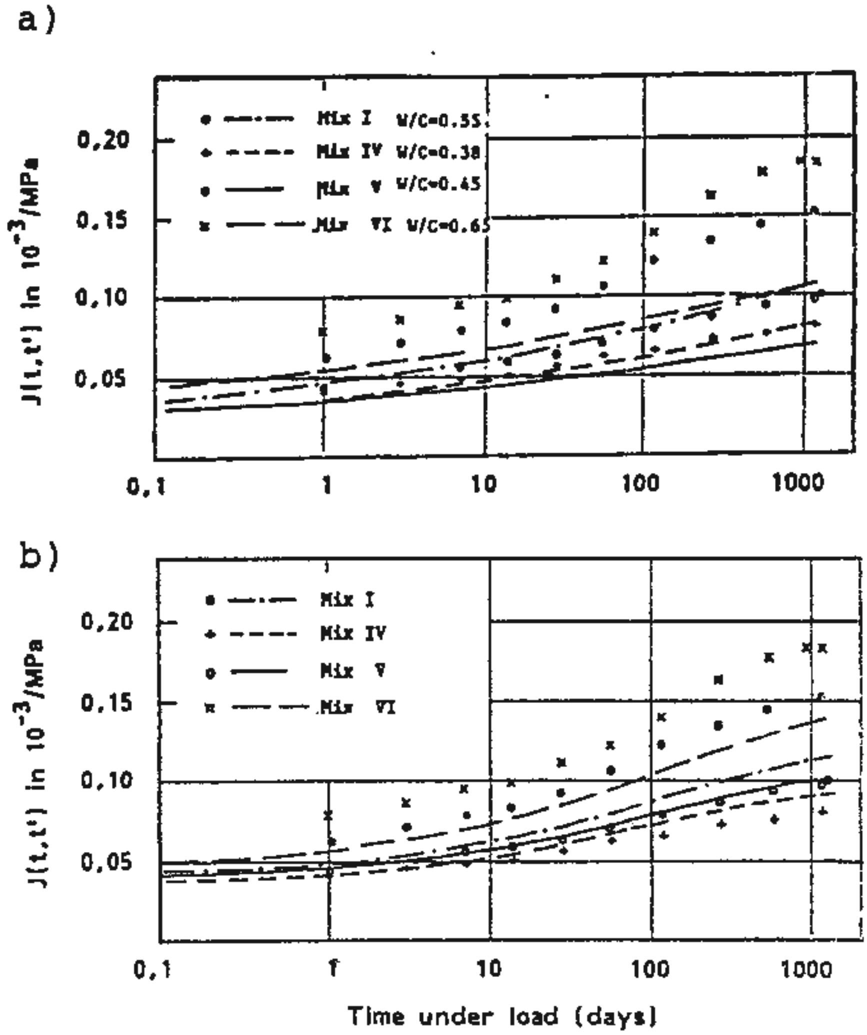

Figure 6. Influence of the w/c-ratio on creep, experimental results of Hummel et.al., (a) in comparison with the BP-model, (b) in comparison with the MC 90 model

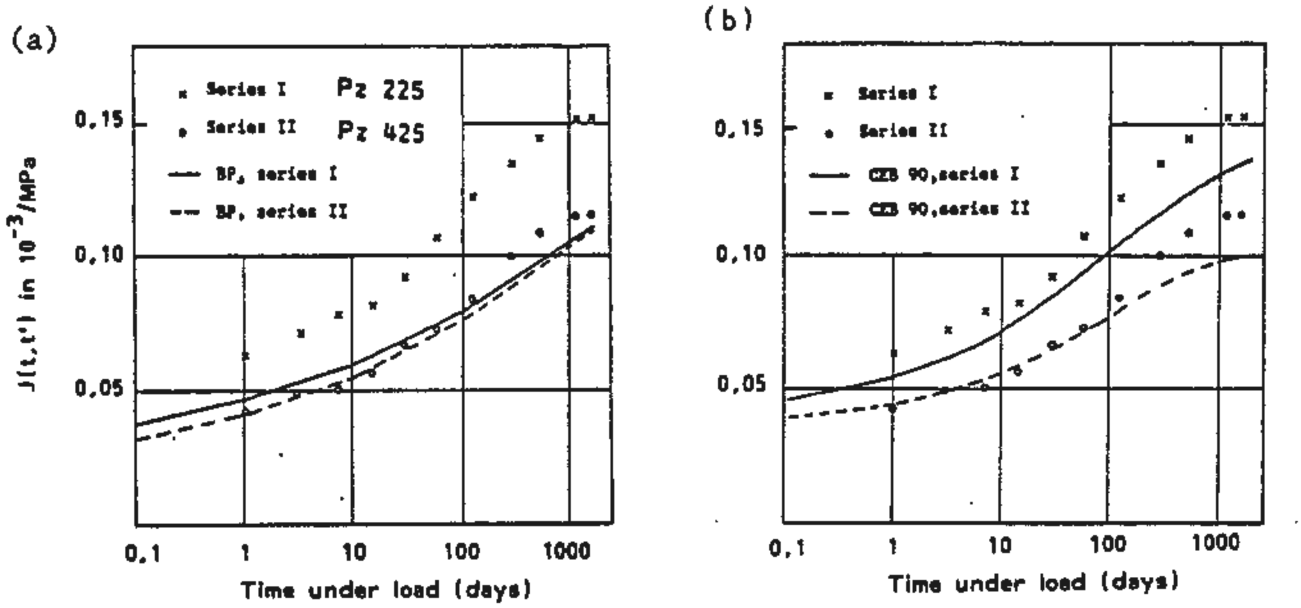

Figure 7. Influence of the cement type on creep, experimental results of Hummel et.al., a) In comparison with the BP-model, (b) in comparison with the MC 90 model.

Although the uncertainty in the prediction of drying creep is large, it is interesting to note that for an experimental series carried out by L'Hermite et.al., (Fig.8), the effect of the relative humidity of the ambient air is quite similarly estimated by MC 90 and the BP-model. The size effect on creep is mainly due to drying creep, and the uncertainty in prediction of this term, makes it difficult to determine the size effect. Fig.9 shows experimental results in comparison with the two models.

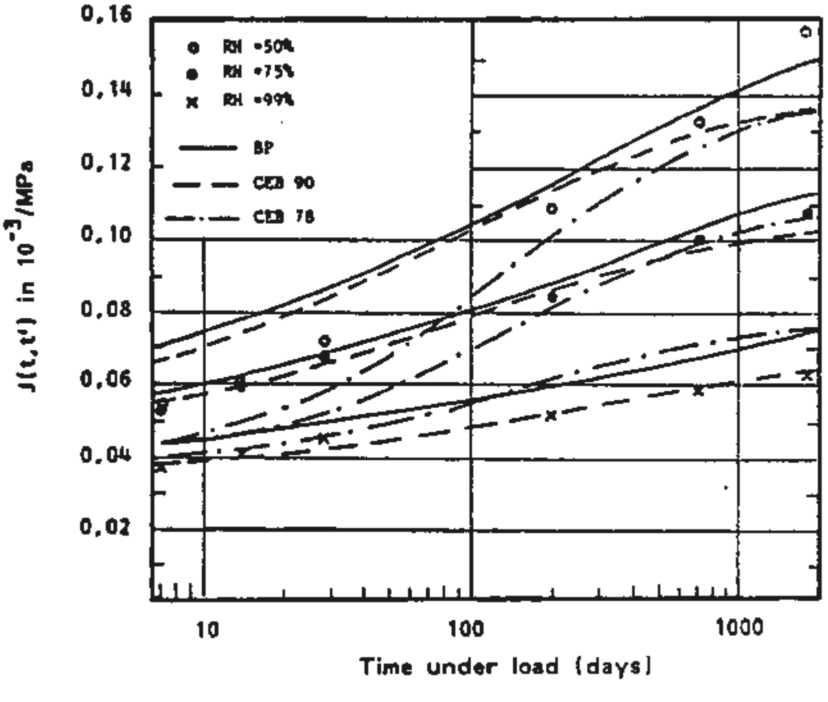

Figure 8. Influence of the relative humidity on creep, experiments of L'Hermite et.al.

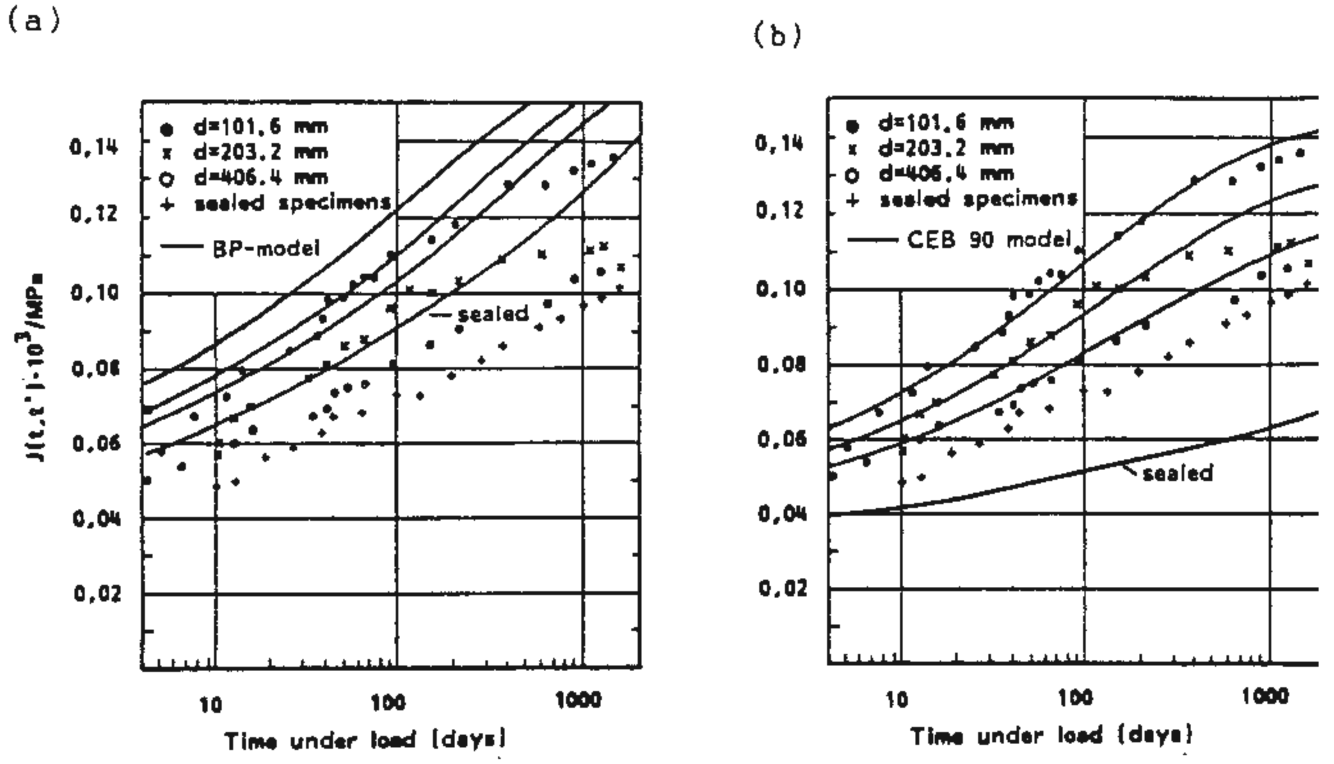

Figure 9. Size effect in creep, experiments of Hansen and Mattock, (a) in comparison with the BP-model, (b) in comparison with the MC 90 model.

In MC 90, the cement type is the only material parameter in the aging function, and with a rapid hardening cement there is less influence of the age at loading. In the BP-model only the w/c-ratio is a parameter in the aging function. The effect of age at loading is increasing with increasing w/c-ratio, which generally is in agreement with experimental observations. Obviously, it is desireable to include both parameters in the models although they then would have to be more involved.

The BP-model is more general and seems to be in better agreement with experimental observations than the MC 90 model when creep at elevated temperatures is considered, Fig.10. The age effect is best estimated by the BP-model when the specimens are exposed to predrying at elevated temperatures. In both models the effect of elevated temperatures on aging of sealed specimens is in accordance with the basic equation for the activation energy theory (Arrhenius equation) also used in hardening technology.

5.Summary and conclusions:

Creep and shrinkage results show that cement and type and w/c-ratio have a significant effect on both these properties.

The MC 90 model seems to better predict the effect of cement type and w/c-ratio on creep and shrinkage when compared to the BP-model.

The BP-model is in better agreement with experimental results than the MC 90 model when creep at elevated temperatures is considered. This is partly due to influence of predrying which only is accounted for in the BP-model.

The simplicity in input parameters makes the MC 90 model favourable in comparison with the BP-model.

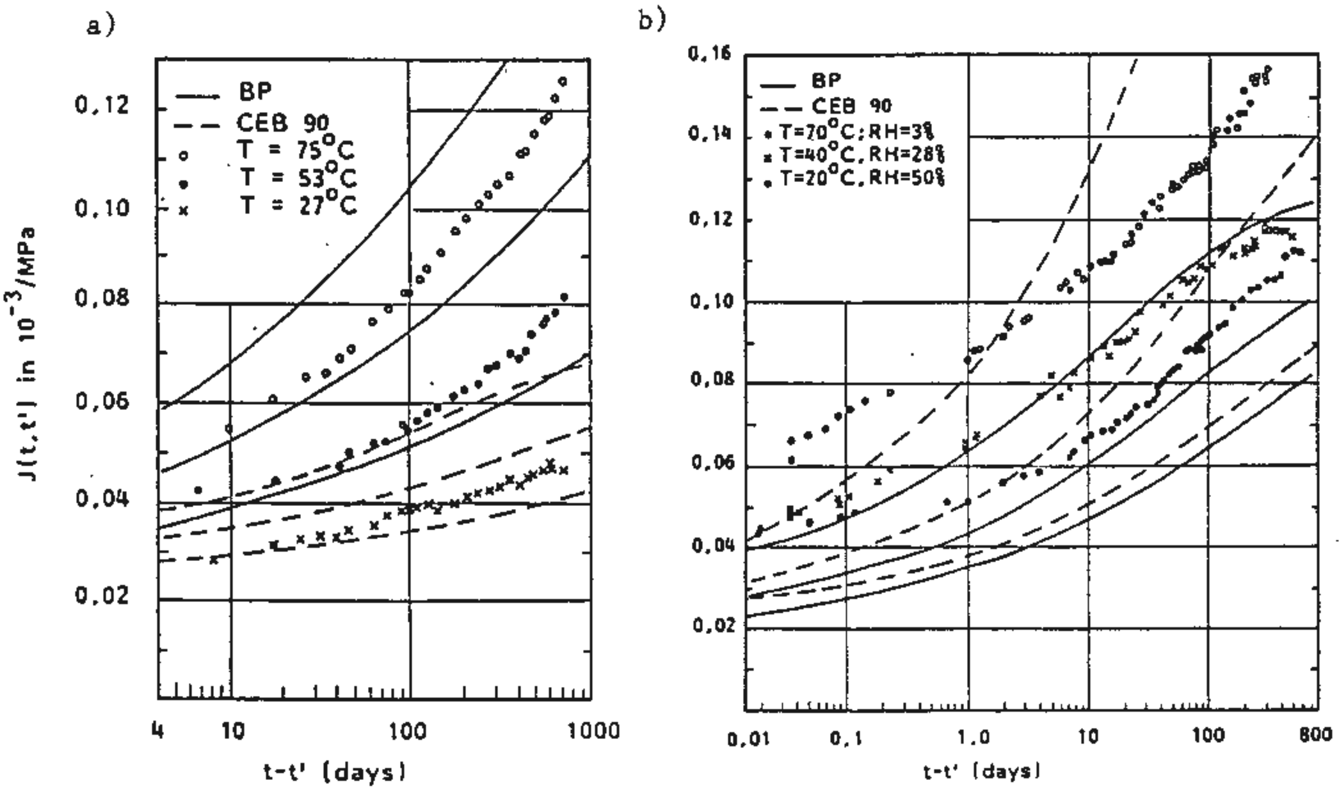

Figure 10. Temperature effect on creep: (a) Experiments of Hannant, sealed specimens, (b) Seki and Kawasumi, specimens exposed to drying.

6.References

1. Kanstad, Terje, "Nonlinear Analysis Considering Timedependent Deformations and Capacity of Reinforced and Prestressed Concrete." Dr.ing. dissertation, Division of Concrete Structures, The Norwegian Institute of Technology, University of Trondheim, May 1990.

2. CEB-FIP Model Code 1990, Comite Euro-International du Beton, September, 1988.

3. Bazant, Z.P. and Panula, L.:, "Practical Prediction of Timedependent Deformations of Concrete, Part I and II," Materials and Structures (RILEM, Paris), Vol.11, Sept.-Oct. 1978, pp 307-328, Part III and IV," Materials and Structures (RILEM, Paris), Vol.11, Nov.-Dec. 1978, pp 415-434, Part V and VI," Materials and Structures (RILEM, Paris), Vol.12, May-June 1979, pp 164-183. "Practical Prediction of Creep and Shrinkage of High Strength Concrete," Materials and Structures (RILEM, Paris), Vol. 17, 1984, pp 375-378.

4. CEB-FIP Model Code for Concrete Structures, Comite Euro-International du Beton, 1978.

5. CEB-FIP, "Evaluation of the time dependent behaviour of concrete," Comite Euro-International du Beton, August 1990.