Construction and Building Materials 105 (2016) 189–195

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

A strength developing model of concrete under sustained loads

Bing Han [a,b,*], Ming-Hui Liu [a], Hui-Bing Xie [a], Yu-Ping Liu [c]

[a] School of Civil Engineering, Beijing Jiaotong University, Beijing, PR China
[b] Key Laboratory of Transportation Infrastructure Safety and Risk Management, Ministry of Transportation, Beijing, PR China
[c] Department of Civil and Environmental Engineering, University of Houston, Houston, TX, USA

HIGHLIGHTS

- Maximum past thickness in concrete was modified considering the effect of sustained load.
- Strength developing rules of concrete under sustained load were explored based on compressible packing model.
- Experiments were executed as a case study to suggest an available process to determine the parameters in the model.

ARTICLE INFO

Article history:
Received 17 July 2015
Received in revised form 11 November 2015
Accepted 9 December 2015

Keywords:
Concrete
Sustained load
Compressive strength
Compressible packing model

ABSTRACT

The strength of concrete will be developed as the age increases. When a sustained load is applied on the concrete, the development rules will be changed. Research on these rules is needed to estimate more rationally the developing strength of concrete used in structures than those without considering the action of sustained loads. In this paper, the development rule of compressive strength of concrete under sustained loads is explored. According to the mechanism assumption, a new model based on the Compressible Packing Model (CPM) for concrete compressive strength is proposed. For calibrating the model, experiments are carried out. Compressive strength of concrete were determined at four different ages and were compared with those of specimens without any sustained loads applied. Comparison of the results by the model and by the experiments show the model presented in this paper can be suit for concrete strength development of concrete under sustained loading.

1. Introduction

It is common sense that concrete structures have to bear sustained loads in their service stage, especially concrete in prestressed structures. As concrete ages, its strength will change. In fact, most of reported researches on the development of concrete strength were based on the condition without sustained load [1]. Although there are some studies that explore the aging characteristics of the concrete material itself without consideration of sustained load, the strength of concrete in a structure, which are very important to evaluate the true behavior of concrete structures, should be studied on the basis of sustained loading conditions.

Sustained loading may change the microstructure of concrete, resulting in the change of the material performance. For example, creep takes place under long-term loading because of the viscous flow of cement gel and the development of internal micro cracks. Some researchers found sustained loading at high stress levels (lower than the compressive strength) may lead to concrete destruction, and the higher stress level is, the shorter time is needed to failure [2]. Because of this, engineers thought that sustained loads had negative effects on concrete strength, and concrete strength was underestimated in practice. However, during the service stage, concrete usually works in its elastic state, which corresponds to stress lower than about 40% of the material compressive strength. Such a low stress is not enough to induce unstable damage, which will decrease strength in concrete, and reversely, the concrete strength increases [3–7]. Nevertheless, all of these studies have not given a clear mechanism on the strengthening effect of sustained loading on mechanical properties.

In fact, concrete is a kind of mixture material with complicated mechanical performance and has significant time-dependent properties. To obtain a more rational description of concrete strength development, lots of research on modeling has been done [8,9]. Mikulic et al. [10] classified all these models into three categories, i.e., (1) models that predict the concrete compression strength

* Corresponding author at: School of Civil Engineering, Beijing Jiaotong University, Beijing, PR China.
E-mail address: bhan@bjtu.edu.cn (B. Han).

http://dx.doi.org/10.1016/j.conbuildmat.2015.12.067
0950-0618/

based on its component; (2) models based on homogenous assumptions, such as models based on maturity methods [11–14] and the degree of hydration concept [15]; and (3) models based on composition and the age of concrete, such as the Exponential Cement Model proposed by Popovics [16] in 1998 and the Compressible Packing Model (CPM) proposed by De Larrard [17] in 1999. Most of these models are semi-empirical and semi-theoretical.

2. Modeling strength development of loaded concrete

Compressible Packing Model (CPM) proposed by De Larrard [17] has a clear description concerning the composition of the concrete material and can be conveniently used to develop a model of concrete for a specific problem. This paper proposes a model for strength development of concrete under sustained loads on the basis of CPM.

2.1. Strength development model based on CPM

Assuming concrete is a kind of binary mixture containing heavy, hard and inert aggregates spread randomly in a cement matrix, it is considered to be somewhat homogeneous. In such a composite structure, the weakest position is located within the cement matrix, which should be the primary focus of attention. A strength development model for a hardened cement matrix is constructed by taking into account the effects of aggregate properties and the topological structure of the aggregates.

Hardened cement matrix is regarded as a kind of porous material whose volume fraction will have an effect on compressive strength [18]. De Larrard [17] found that there is more unhydrated content in cement matrix with low water cement ratio, and suggested a 28-day compressive strength model as follows [17]:

$$f_{\mathrm{m}} = 11.4 R_{c28} \left(\frac{V_c}{V_c + V_w + V_a} \right)^{2.85} \tag{1}$$

where f_m is the 28-day compressive strength of cement matrix curing hermetically (MPa); R_{c28} is 28-day standard strength of cement (MPa); V_c, V_w and V_a stands for volume of cement, water and aggregate, respectively (mm^3).

A unified physical parameter named maximum paste thickness (*MPT*) was proposed by De Larrard to take account for the maximum size and volume fraction of aggregates. Image in a dry accumulation of aggregates, the maximum stress should occur at junction points between aggregates [19]. If cement matrix is injected into the accumulation, the aggregates should spread evenly, and a layer of cement matrix would form between two adjacent aggregates. The cement matrix layer is under high stress, i.e. *MPT*. The forming process of the *MPT* is shown as Fig. 1 [17].

MPT is written as

$$MPT = D\left(\sqrt[3]{\frac{g^*}{g}} - 1 \right) \tag{2}$$

where D is the maximum size of the aggregate (mm); g is volume of aggregate in unit volume after spreading (mm^3); g^* is the aggregate volume before the cement matrix injected, also called stacking density (mm^3).

Concrete strength development can be expressed by [17]

$$\begin{cases} f_{cm}(t) = 13.4 R_{c28} \left[A \lg(t/28) + \left(1 + \rho_c \frac{w+a}{c_{eq}(t)} \right)^{-2.85} \right] MPT^{-0.13} \\ c_{eq}(t) = c\left[1 + 1.1 \left(1 - \exp\left(-(B \lg t + P) \frac{f_a}{c} \right) \right) \right] \\ f_c(t) = \frac{p f_{cm}(t)}{q f_{cm}(t) + 1} \end{cases} \tag{3}$$

where ρ_c is cement density (kg/m^3); t stands for time (d); A is constant related to cement properties; B and P are constant related to fly-ash properties; p and q is constant related to aggregate type; c_{eq} is equivalent cement mass in concrete at a given age

$$c_{eq} = c[1 + \Psi(f_a/c)] \tag{4}$$

where c refers to cement mass (kg); f_a stands for fly-ash mass in unit volume of concrete (kg); Ψ can be written as seen in Eq. (5)

$$\Psi = \Psi_{\max}\left[1 - \exp\left(-K_p \frac{f_a}{c} \right) \right] \tag{5}$$

where K_p is activity coefficient reflecting strength contribution of fly-ash, and linear relation with $\lg t$; $\Psi_{\max}$ is a coefficient related to maximum mass of lime precipitation, and optimal value is suggested as 1.10.

2.2. Modified CPM considering sustained load

2.2.1. Modification for physical effects of sustained loads

On the basis of the analysis above, concrete compaction caused by sustained load mainly occurs in the cement matrix. As a result, the volume of the cement matrix is reduced, and the aggregate volume can be considered unchanged based on the assumption that aggregates are incompressible. Thus the aggregate content in a unit concrete volume, g, will increase, inducing an *MPT* decrease.

According to CPM, concrete can be seen as a stressed accumulation of dry aggregates injected into cement matrix in batches [17]. The initial stress in the pressure system is called σ_0, as shown in Fig. 2. It should be a constant depending on the characteristics of concrete itself and may also be related to the internal energy of concrete at the loading age, or the strength of concrete or topological properties between different components. When the accumulation has no load action, the volume expands uniformly along the grid posed by the center of gravity of the aggregates during the process of injecting cement matrix, and *MPT* is formed at the junction point of two aggregates. The expansion coefficient is set as λ. During the expansion, outside work acts on the system overcoming σ_0, and the external work is set as W. The expansion coefficient becomes λ' after the injection of cement matrix when stress is equal to αf_{c0}, and the maximum thickness of paste changes to MPT', where $\lambda' < \lambda$ and $MPT' < MPT$. During the process, outside work, W', acts on the system to overcome $\sigma_0 + \alpha f_{c0}$. In Fig. 2, the comparison of *MPT* formations in the two situations is shown.

Now take a coarse aggregate in the *MPT* as an example based on the spherical model in which aggregates are supposed to be in a shape of sphere. In an unstressed state, force on the coarse aggregates is $\sigma_0 \pi d^2/4$ and the external forces do negative work to result in a displacement of *MPT*. In a stressed state, force on the coarse aggregates is $(\sigma_0 + \alpha f_{c0})\pi d^2/4$ and the negative work leads a displacement of MPT'.

Supposing the values of external work are the same regardless whether or not load is applied, that is $W = W'$. The equivalence relation can be expressed as

$$\begin{aligned} & -\sigma_0 \tfrac{\pi d^2}{4} \cdot MPT = -(\sigma_0 + \alpha f_{c0}) \tfrac{\pi d^2}{4} \cdot MPT' \\ & \Rightarrow \ MPT' = \tfrac{\sigma_0}{\sigma_0 + \alpha f_{c0}} MPT \end{aligned} \tag{6}$$

where σ_0 stands for initial stress in the accumulation and is a constant related to concrete properties (MPa); $\alpha = N/(f_c A_c)$; N refers to external force (N); f_c refers to concrete compression strength at a given age (MPa); A_c refers to cross-section area of concrete member (mm^2); f_{c0} is strength of concrete at the time of loading (MPa).

Substitute Eqs. (6) into (3), and the physical effect of load on strength development of concrete can be reflected by stress factor $[\sigma_0/(\sigma_0 + \alpha f_{c0})]^{-0.13}$.