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Experimental investigation on the fundamental behavior of concrete creep

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HIGHLIGHTS

- A new method was presented to test the fundamental behavior of concrete creep.
- It is observed that concrete exhibits obviously hysteretic recovery.
- It is observed that the concrete creep does not only depend on sustained loads.
- The creep strain during the loading process is distinguished from initial strain.
- It is observed that the time-dependent strain peaks under load duration.

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ABSTRACT

Concrete is one of the most widely used materials in modern civil engineering construction. Concrete creep is traditionally defined to be a kind of time-dependent behavior exhibited by concrete under sustained constant loads. In this article, a new method is proposed to test the short-term creep of concrete and the deformation state after unloading process. The test results indicate that after loading, regardless of whether the constant load is sustained or not, the specimen exhibits a hysteretic recovery after unloading, which challenges the traditional definition of concrete creep. In addition, we first observed that the fundamental time-dependent strains of concrete, which can be separated from concrete creep under sustained load, could peak in several minutes and begin to fall. The long-term creep mainly results from unrecoverable deformation, which arises as the recoverable deformation is gradually transformed into unrecoverable deformation through micro-damage accumulation. The hysteretic recovery and time-dependent behaviors which were discovered reveal the fundamental viscoelastic origin of concrete creep.

1. Introduction

Concrete is one of the most widely used materials in modern civil engineering construction. Although an enormous amount of concrete structures have been constructed over the past 100 years, concrete consumption is expected to continue rising with the prolonged tide of infrastructure construction. According to the report from McKinsey & Company on infrastructure, the global demand for new infrastructure could amount to more than $90 trillion from 2015 to 2030, which almost results in tripling the value of the world's infrastructure from $50 trillion at present [1]. Besides, the American Society of Civil Engineers estimates the demand around $3 trillion in American infrastructure investments during the coming decade [2]. The creep property of concrete leads to development of stresses, cracking and excessive deflections which compromise the durability and sustainability of concrete structures [3,4]. In the United States, concrete creep is partly responsible for an estimated $78.8 billion for highway and bridge maintenance annually requirements [5].

Creep of concrete has already been studied for a century; Woolson [6] was perhaps the first to describe, in 1905, the "flow of concrete under pressure." During about a century of development, a large number of experimental and theoretical investigations of concrete creep have been conducted in fields including analysis of influencing factors, microscopic mechanisms, prediction models, etc. In the frame work of the superposition principle proposed by Boltzmann in 1878 [7], creep strain can be expressed as the time integral over all stress rates multiplied with creep function, as shown in Eq. (1).

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$$\varepsilon(t) = J_0\sigma + \int_0^t J(t-\tau)\frac{d\sigma(\tau)}{d\tau}d\tau \quad (1)$$

Theoretically, the creep strain can be calculated for arbitrary load conditions based on superposition principle. However, it is difficult to distinguish creep and elastic strain during the initial loading process. Generally, the definitions of concrete creep are presented based on test phenomenon, as follows:

(1) When a load is applied on a concrete specimen, the specimen first shows an instantaneous deformation, which is then followed by slow further increase of deformation. This slow increase of deformation is called creep [8];
(2) A material shows creep if its deformation increases with time under a constant stress [9];
(3) The time-dependent increase in strain under constant load taking place after the initial strain at loading [10];
(4) Under sustained compressive loads, concrete will continue to deform for long periods of time. After the initial deformation occurs, the additional deformation is called creep [11].
(5) The load-induced deformation of concrete includes two parts, the first is initial deformation at loading, and the other is the deformation increase under load duration. The latter is called creep [12].

The provenances of the above definitions include authoritative academic monographs [8,9], widely used design standard [10] and American and Chinese textbooks [11,12]. Besides that, the concrete design standards and textbooks of other countries reflect some shortcomings on the understanding and research of concrete creep.

Firstly, the concrete creep is always defined as the increase in deformation under a constant or sustained load. The deformation during the loading process is regarded as initial or instantaneous deformation, separate from creep deformation. Thus, the creep of concrete only occurs under constant or sustained loads, after an initial or instantaneous deformation during the loading process. In fact, as the external load cannot be applied instantaneously, the deformation during the loading process cannot be simply treated as initial or instantaneous deformation, either. Moreover, only the deformation under load duration process can be tested, as the 'creep' during loading process is difficult to observe in tests even using the nano-indentation method [5], so the time-dependent deformation during the loading process is always ignored. Some scholars have probably realized this problem, Irfan-ul-Hassan et al. [13] distinguish the elastic deformation and creep deformation during the loading process, by testing the elasticity of material in the unloading process. However, most researchers, engineers, and students in civil engineering still adopt such definitions of concrete creep from the textbooks, academic monographs, and design standards as mentioned above.

On the other hand, concrete creep is always studied as a long-term characteristic under sustained loads; thus, it can be found that in the Database of Laboratory Creep and Shrinkage established by Bažant and Li [14], the typical duration of creep experiment ranges from several days to even years, while research into short-term creep properties does not attract wide attention. Vandamme and Ulm [5,15] tested minute-long creep of calcium-silicate-hydrates (C-S-H) and revealed how long-term creep characteristics can be estimated from short-term tests. Irfan-ul-Hassan et al. [13] investigated minute-long elastic and creep properties of young cement paste with experiment. Knigsberger and Irfan-ul-Hassan [15] provided the non-aging creep properties of the hydrate phase based on the three-minute-long creep tests of cement pastes. The short-term creep has attracted some attention, however, the relevant experimental study focused on the C-S-H and cement paste. The existed experimental data regarding short-term creep of concrete are still insufficient [5,13,15]. However, in engineering practice, cracking is highly dependent on creep in concrete at early age, especially in super high-rise buildings and massive concrete structures [16,17]. Therefore, short-term creep of concrete deserves special attention.

In addition, the long-term testing of concrete creep is complicated by multiple factors. Fig. 1 shows the details of concrete strain under long-term load duration, in which drying creep depends on environmental temperature and humidity and basic creep depends more on the mechanical properties and constituents [10]. During long-term loading, the properties of concrete and its environment change continuously. Although many theories describing mechanisms of concrete creep have been presented [18-22], however, none of these theories can explain all the experimental observations.

In conclusion, three problems of concrete creep are noteworthy:

(1) Creep is always defined as the increase of deformation under constant or sustained loading, in which the time-dependent deformation during the loading process is ignored.
(2) The short-term creep properties of concrete have not attracted wide attention, so relevant data is still scarce.
(3) The long-term testing of concrete creep is complicated by multiple factors, but its fundamental time-dependent behavior has not been sufficiently studied.

This calls for the development of novel, improved experimental protocols for understanding and defining concrete creep, and this article is devoted to exactly such developments.

In order to address the problems of the definitions as discussed above, we need to study concrete creep from a new perspective. As shown in Fig. 2a, when the minute-long creep of concrete is tested, an unloading process is conducted, too. See Fig. 2b, in which emphasis is placed on the deformation behavior of concrete after quick unloading. The hysteretic recovery is tested with a high sampling frequency until the deformation becomes stable.

Based on the deformation properties observed during the unloading process in this experiment, it can be found out whether concrete creep only depends on constant or sustained loading or not. In the traditional definition of creep, only instantaneous deformation occurs during the loading process, and there is no creep deformation without extended load duration, which means that the deformation of concrete would recover fully and instantaneously after unloading. But in this experiment, if the creep deformation occurs during the loading process, without a constant, prolonged load, then the deformation of concrete would recover gradually after an instantaneous unloading, which indicates that the concrete creep does not depend on constant or sustainable load duration.

It should be noted that this hysteretic deformation recovery is different from the creep recovery of concrete. Generally, the creep recovery is a long-term property of concrete, which is similar to the creep property, with the typical test time ranging from several days to years. Therefore, creep recovery of concrete is also complicated by multiple factors, such as stress level, duration, loading age, external environment, mechanical properties and constituents of concrete [23–27], etc. In this study, the hysteretic recovery of concrete will be tested for several minutes or less, in order to reduce the influence from the above factors. In addition, once the hysteretic recovery has finished, the residual deformation can be defined as the plastic deformation.

Over a short period of time, the observed creep and hysteretic recovery more closely reflect the viscoelastic behavior of concrete itself. Viscoelastic theory has also been employed for concrete creep prediction [28]. If the viscoelastic behavior of concrete does