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Flexural creep in plain concrete: State of the Art

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Abstract

Concrete, being a viscoelastic material, creeps with time causing additional strains and deflections in flexural members. Most of the studies in creep of concrete are based on long-term tests on plain concrete standard cylinders under axial compression, very limited studies have been reported on creep of concrete in flexure and direct tension. Whether the mechanism of creep in tension is different from creep in compression is still being debated. Numerous studies have been reported in the literature showing varied results with regard to the effects of creep in direct compression, direct tension and flexure. This paper provides a brief review of various creep tests on plain concrete reported and attempts to understand the effects of various parameters on the creep behaviour of concrete. Some studies reported that the creep in tension is higher than that in compression, whereas a few others obtained contradictory results from creep tests. This may be attributed to the fact that the relative creep behaviour in tension and compression is highly sensitive to the material composition, exposure conditions and loading level. The studies by various researchers on flexural creep in plain concrete are also discussed.

Keywords: Flexural Creep, Plain Concrete, Review

1. Introduction

Concrete is one of the most widely used construction materials around the world and it is being increasingly adopted for lifeline structures like bridges which are designed for a life span of at least 100 years. Hence a good understanding of the long-term behaviour of concrete is crucial. Since concrete is a viscoelastic material, it undergoes creep and shrinkage with time. Accurate prediction of the creep and shrinkage strains in concrete is a major challenge because of the various uncertainties involved in the material and the environmental conditions. Even after decades of research in the creep behaviour of concrete, the prediction models keep evolving to attain better accuracy. Even the mechanism of concrete creep is still being debated, few of which are discussed in this study.

In addition, creep in concrete flexural members is even more complex since there is both compression and tension across the section in the same member. Therefore, to understand flexural creep, the creep behaviour of concrete in tension and compression needs to be studied first. This paper provides a concise review of the concrete creep studies in compression, tension and flexure of plain concrete reported in literature. Studies on plain concrete subject to bending in literature are limited as most of the recent research is focussed on bending creep in reinforced concrete [1-3] and prestressed concrete [4-6].

2. Creep Mechanism

Many possible creep mechanisms in concrete have been proposed by researchers over time. Neville et al [7] have summarized the various mechanisms, some of which are given below:

Viscous and visco-elastic flow theories have been used by few researchers to describe concrete creep behaviour since concrete is a viscoelastic material and viscous flow occurs in concrete. This theory put forward first by Thomas [8] considers concrete to constitute of a cementitious material which is highly viscous and aggregate which is inert. Main objections to this theory are that, for pure viscous flow, the volume should be constant which is not the case in creep and it also requires a proportionality between stress and strain which is true to some extent.

Seepage theory is one of most accepted theories for creep. This theory accounts for the volume change and the partial immediate recovery of creep following load removal.

As per this theory, upon loading, creep occurs due to seepage of gel water. This theory is still being debated upon in literature as there are many arguments supporting as well as opposing this theory. Hannant [9] suggests that the predominant factor for the cause of creep is the shear between the crystalline surfaces. Various other theories like activation energy approach, thermodynamic approach etc. have also been proposed by researchers over time.

Most of the accepted theories like seepage theory, visco-elastic flow theories etc. do account for creep of concrete in compression, but for creep in direct tension and flexure, a

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combination of different mechanisms are being adopted in literature for describing the behaviour satisfactorily.

Many studies in literature assume that the mechanism of creep in compression and tension are the same. This assumption has also been questioned by some researchers based on the observations from experimental studies. Ward and Cook [10] proposed that in addition to seepage, microcracking plays a major role in tensile creep of concrete. Domone [11] has interpreted the experimental observations in tensile creep of concrete using both seepage theory and viscous shear theory satisfactorily. Altoubat and Lange [12] considered the solidification theory to develop a basic creep model for tensile creep of concrete. A consensus has not yet been reached regarding the creep mechanism.

Experimental data available in literature on concrete creep in tension is limited when compared to the research on creep in compression. The main reason for this can be attributed to the fact that concrete being weak in tension is rarely designed to be subjected to direct tension. The practical difficulty of achieving a state of direct tension in concrete in the experiments also adds to the limited data in tension creep.

3. Creep in tension and compression

The difference in the creep behaviour of concrete under tension and compression has been studied by numerous researchers and the results are mostly contradictory. Brooks and Neville [13] compared the concrete creep behaviour in tension and compression by conducting creep tests on plain concrete specimens of same mix subjected to a stress to strength ratio of 0.3.

It was observed that if the specimen is loaded after drying has taken place, then the total creep in tension is less than that in compression whereas, if drying is allowed to occur after loading, the creep behaviour in tension and compression is almost similar. The experimental study also showed that age of concrete reduces basic creep in compression but doesn’t appreciably reduce basic creep in tension.

Atrushi [14] also observed that, although the initial creep rate in compression is higher than tension, the rate of creep in compression reduces with time whereas the reduction in creep rate in tension is comparatively less. One possible reason for this suggested by Atrushi [14] is that the stress to strength ratio in compression actually reduces with time due to the gradual gain in compressive strength of concrete whereas the strength gain in tension is very less and hence does not cause any appreciable reduction in stress to strength ratio. In the experiments conducted, specific creep in compression was observed to be higher than that in tension. Another important reason given in the study for the different behaviour is the assumption that autogenous shrinkage strains and creep strains are independent.

Similar results were also obtained by Rossi et al [15] in the experimental study conducted. The specimens were loaded at an age of 64 days and the stress to strength ratios considered were 0.5 and 0.7. Basic creep in compression was observed to be higher than tension creep. On the contrary, when drying is allowed, both tension and compression creep are similar. In addition, Rossi et al [15] also reported that there is a greater difference between basic creep in tension and in compression when the concrete is younger. Microcracking and water diffusion theories have been used to interpret the creep behaviour.

Briffaut et al [16] reported that, based on the experimental results, for the considered mix in the study, the basic creep behaviour in tension and compression are similar. The specimens were protected from drying and the stress to strength ratio was 0.3. The loading age for this study varied from 24 hours to 120 hours.

A contradiction to these studies was put forward by Kristiawan [17] as the experimental study showed that for the same stress to strength ratios, tensile creep is about seven times that of compressive creep for the same concrete and on the basis of same stress, tensile creep is almost twice that of compressive creep. The study was done on bobbin shaped specimens loaded at an age of 7 days and subject to drying.

The experimental studies by Forth [18] also showed higher tensile creep. Forth [18] did creep tests on concrete under tension and compression subjected to the same stress and stress to strength ratios. 40% cement was replaced using GGBS (Ground Granulated Blast Furnace Slag). Different ages of loading were considered in the study. It was observed that at equal stresses, when loaded at an age of 28 days, tensile creep can be up to several times greater than compressive creep. A possible error in this observation suggested by Forth [18] is that since compressive stress applied is very low (less than 5% of strength), there is nonlinearity in the creep behaviour which affects the comparison. At low stresses, when loaded as early as 3 days, the compressive creep was observed to increase such that the ratio of tensile to compressive creep will be more similar to unity.

Similarly, Illston [19] observed that the rate of creep in tension is much higher than compression initially but gradually reduces with time and may become equal to or lesser than the rate in compression.

Glanville and Thomas [20] observed similar creep behaviour in tension and compression, the specimens being subjected to same stress, variable humidity and loaded at an age of 30 days. The study was on total creep which includes drying also. However, Davis et al [21] reported that under the same stress, the rate of creep in tension is higher initially and decreases with time; this is in line with the experimental results by Kristiawan [17] and Illston [19].

Wei et al [16] proposed that the relative behaviour of tension and compression creep is sensitive to water cement ratio of the mix based on the experimental results obtained. When drying is allowed, it was seen that for lower water cement ratios (0.3), tensile creep magnitude was higher than compressive creep, whereas for higher water cement ratios (0.4,0.5), both tensile and compressive creep magnitude were similar. But when the specimen is sealed, for all water-cement ratios, compressive creep was higher than tensile creep.

Based on the review, it is understood that the relative behaviour of tensile and compressive creep is very sensitive to the mix, test set-up, exposure conditions and loading age. Most of the studies show that tension creep and compression creep behaviour is similar. Both are sensitive to the same parameters like loading age, stress, humidity etc. In some cases, when drying is allowed, the relative behaviour of tension and compression creep is observed to change, mostly tension creep becoming higher [13, 15, 22].

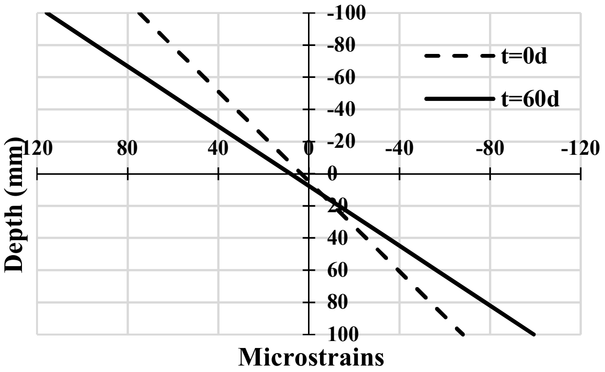

Fig. 1. Measured strains along depth with time [23]

4. Creep in Flexure

Behaviour in flexure constitutes of both compressive creep and tension creep due to the stress gradient across the section. Therefore, the flexural creep behaviour will be a resultant of compression and tension creep. Few studies have been reported in the literature, that conducted flexural creep tests along with tensile and compressive creep tests.

Rossi et al [23] conducted compressive, tensile and bending basic creep tests on the same concrete loaded at an age of 64 days. Specimens were loaded at 50 and 70% of their corresponding strengths. For the bending test, strains were monitored across the depth and specific creep curves were developed from all the tests. Test results showed that the strain distribution across depth remains linear with time as shown in Fig.1. Due to the similar strain distribution observed in the extreme fibres, development of additional tensile stresses to maintain strain compatibility was proposed by Rossi et al [23].

Similar study was conducted by Ranaivomanana et al [24]. In this study, the stress to strength ratio was maintained as 0.5 and all specimens were of the same concrete (high performance concrete) and loaded at an age of 28 days. The specimens were sealed to ensure that no drying occurs. The test duration was 30 days. The strains were monitored across the depth in the bending specimen and a slight shift in neutral axis is noted as shown in Fig. 2.

Specific creep curves for direct compression, direct tension, flexurally induced tension and compression were developed from strain data and is shown in Fig. 3. It can be seen that, the creep in compression is of the highest magnitude and that in tension is the lowest. The creep magnitude in tension reduces after a point of time which can be due to interaction with shrinkage as they are of opposing nature to tension creep. The flexural creep curve lies in between that of the direct compression and direct tension curves. The same test was repeated for different stress to strength ratios in tension, compression and flexure by Rainovomanana et al [25]. It was seen that for different stress levels, the specific creep curves are different in direct compression and this can be attributed to the possibility of non-linear creep occurring at 50% stress level [25]. However,in tension, scatter was seen in the specific creep curves which can be due to the high sensitivity of concrete in tension [25].

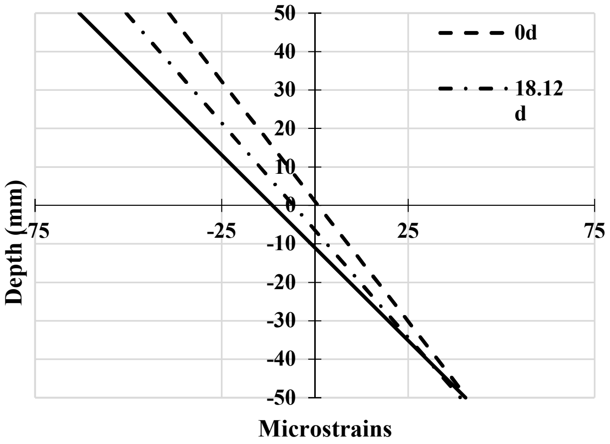

Fig. 2. Measured strains along depth with time [24]

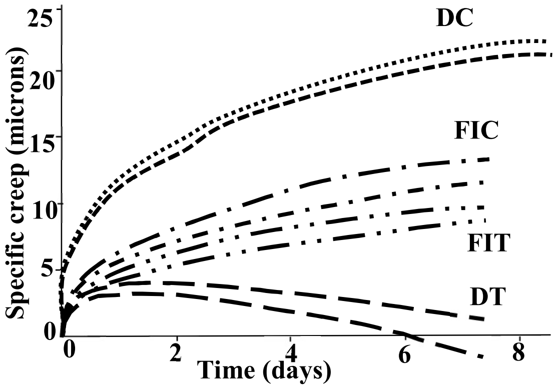

Fig. 3. Specific creep curves for direct compression creep (DC), flexurally induced compressive creep (FIC), flexurally induced tensile creep (FIT) and direct tension creep (DT) [24]

In flexure, the specific creep curves in tension and compression were similar for different stress levels except for flexural compression at 30% stress level (30% of tensile strength) as shown in Fig. 4.

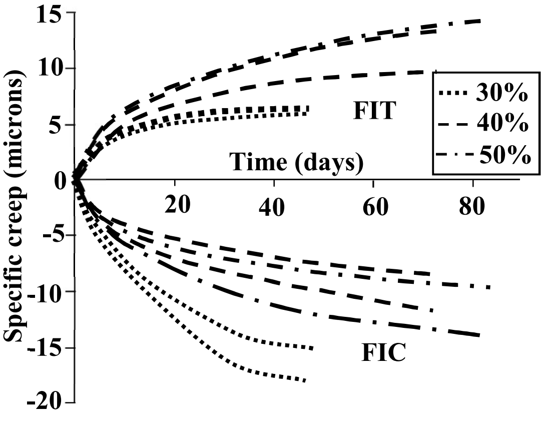

Fig. 4. Specific creep curves for flexural compression and flexural tension. [25]

This can also be attributed to the possible nonlinear behaviour that may occur at such low compressive stresses [18].

Wei et al [22] conducted direct compression, direct tension and flexural creep tests simultaneously on the same concrete loaded at an age of 7 days and tested for a period of 28 days. Three different water-cement ratios of 0.3,0.4 and 0.5 were considered for the study. The stress to strength ratio of 0.4 was kept constant in all the specimens. For the flexural creep test, midspan deflection of the beam was monitored for the entire test duration and has been used to generate the specific creep curves. This implies that the flexural creep curve developed in this study represents a resultant of the interaction between tension and compression creep.

For the specimens with a water cement ratio of 0.4, it was observed that the initial rate of creep for flexure was almost similar to that of compressive creep as shown in Fig .5 but with time, the flexural creep rate reduced whereas the compressive creep rate kept increasing. For the specimens with a water cement ratio of 0.4, it can be seen that the flexural creep rate is initially higher and keeps increasing with time, its magnitude being greater than that of compressive and tensile creep as shown in Fig. 6.

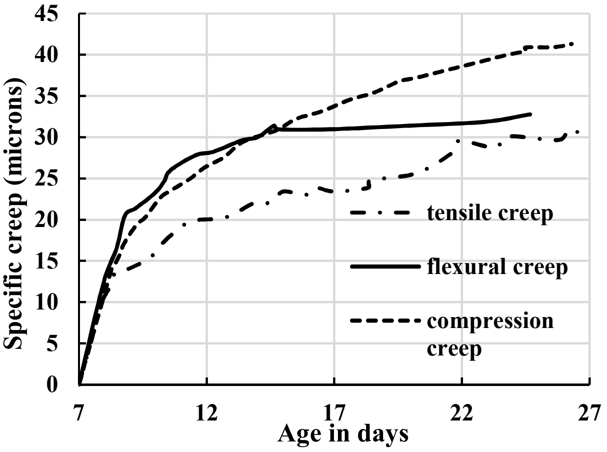

Fig. 5. Specific creep curves (basic creep) for direct tension, direct compression and flexure for mix with w/c 0.3. [22]

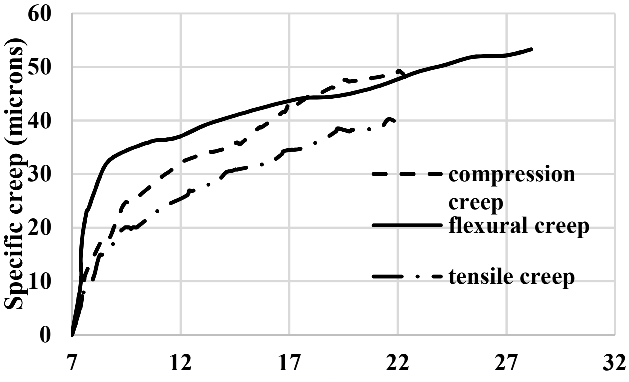

Fig. 6. Specific creep curves (basic creep) for direct tension, direct compression and flexure for mix with w/c 0.4. [22]

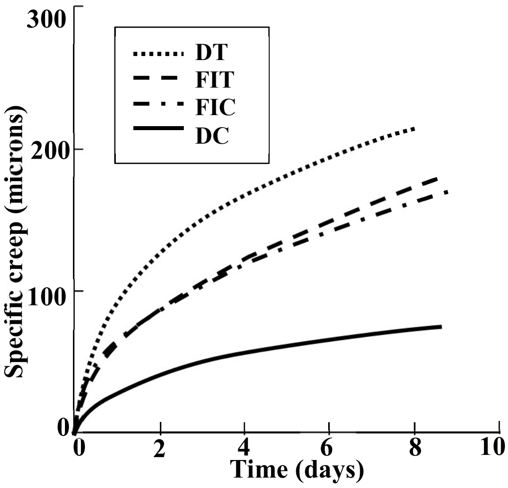

Fig. 7. Specific creep curves for direct tension (DT), direct compression (DC), flexural compression (FIC) and flexural tension (FIT). [26]

Wei et al [22] observed that the flexural creep of mix with 0.4 w/c was 65% greater than that with w/c 0.3 thereby indicating that flexural creep is senstive to water cement ratio. Total creep in flexure, tension and compression was not compared in the study as the volume to surface area ratios for the corresponding specimens are different.

Lee et al [26] performed creep tests in tension, compression and bending. All the specimens were subject to drying and every test had control specimens for shrinkage measurement. The test duration was 85 days. The experimental study showed that the flexural tensile creep and flexural compressive creep was similar and the neutral axis remained almost constant. The flexural creep magnitude was less than that of direct tension and more than that of direct compression as shown in Fig. 7. For all the cases, direct tensile creep was higher than direct compression creep. Since the specimen sizes for bending and direct tension or compression tests were different, the comparison of their creep behaviour in this study is questionable.

5. Conclusions

The review of studies in tension and compression creep shows that different experiments give contradictory results and even though few studies are in agreement with each other, it is impossible to arrive at a generalized conclusion regarding the behaviour of concrete creep in tension and compression. One common observation from different studies considered is that the relative behaviour of tension and compression creep is highly sensitive to drying. However, the results from different experiments cannot be compared due to the difference in specimen sizes, exposure conditions, test set-up etc. Therefore, to get a reliable comparison between tension and compression creep, an extensive experimental study considering various parameters is required.

In the case of flexural creep, most of the studies show that flexural creep magnitude lies in between that of direct compression and direct tension. The neutral axis remains almost constant and the magnitude of flexural tensile creep and flexural compression creep is almost same. Even though most of the studies indicate that compression creep is higher than flexural creep, when the water-cement ratio is increased, flexural creep becomes higher than compression creep [22]. Most of the experiments reported in flexural creep are of a test duration less than 30 days. This limitation makes it questionable to conclude the overall behaviour in flexure based on these tests, as with time, the behaviour may change.

Another aspect that needs attention in flexural creep is that, when flexural compression and flexural tension is compared, the tensile portion will mostly be within linear creep range as the stress to strength ratio is based on flexural strength, but the compression region stress to strength ratio will be too low which can cause non-linear behaviour. Therefore, more tests consisting of different stress to strength ratios and both basic and drying creep specimens subjected to constant stress for a minimum duration of one year are required to arrive at a definitive conclusion on the flexural creep behaviour.

Disclosures

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