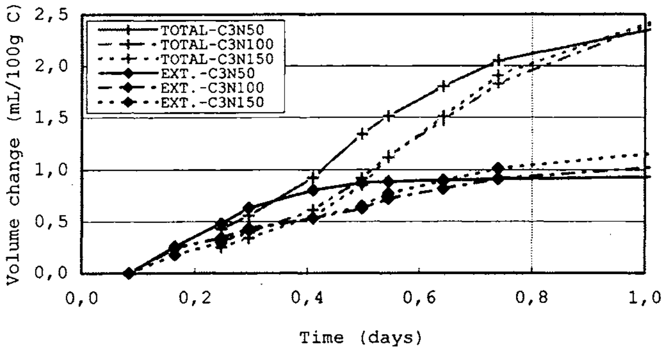


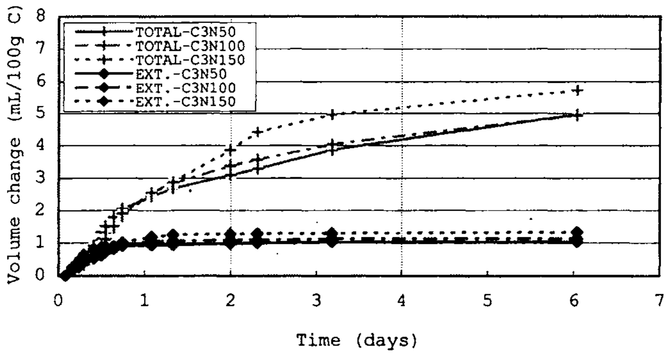


Figure 7 - Shrinkage test results (*C3* and naphtalene-based superplasticizer)

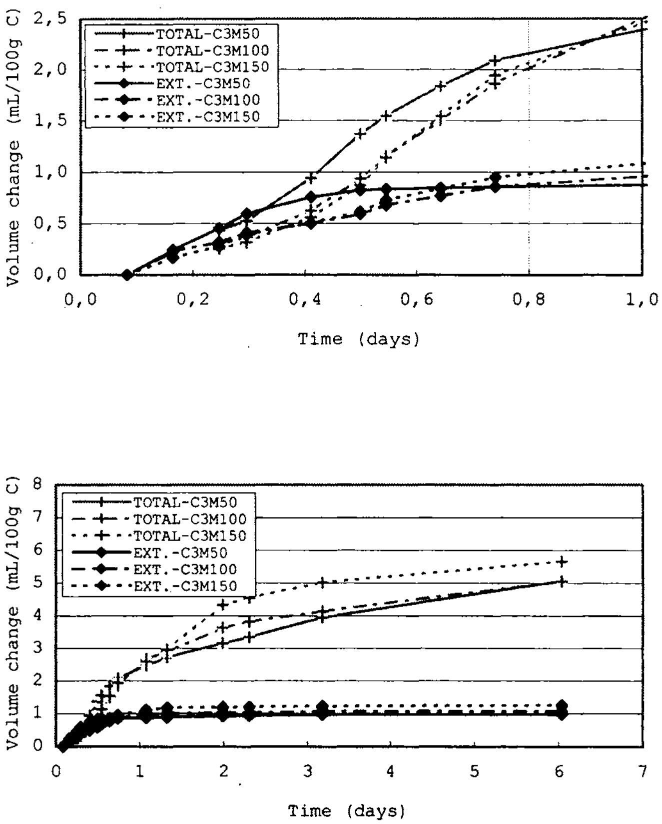
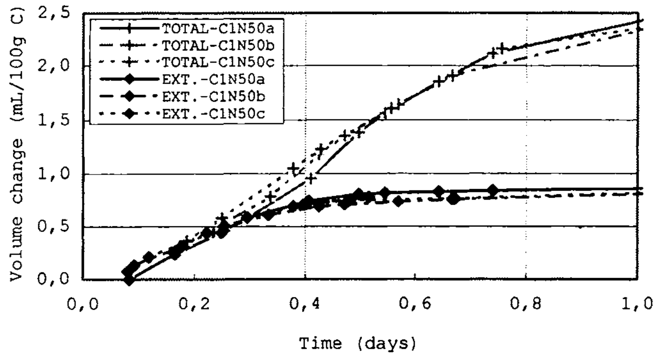


Figure 8 - Shrinkage test results (*C3* and melamine-based superplasticizer)



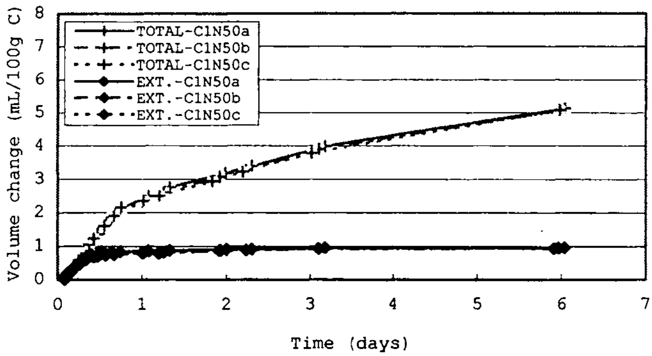


Figure 9 - Repeated shrinkage tests (*C1* and naphtalene-based superplasticizer)

Grip-Specimen Interaction in Uniaxial Restrained Test

by S. A. Altoubat and D. A. Lange

Synopsis: Restrained tests are used to evaluate the risk of early age cracking and the cracking sensitivity of concrete mixtures. One test that has become common in recent years is the active uniaxial restrained test in which the length change due to shrinkage is recovered by applying external load to maintain the concrete sample at constant length. The length change is measured by linear variable differential transformer (LVDT), which is used as the control signal in this test. In such tests, the dog-bone geometry is used to grip the ends. To ensure a fully restrained test, the LVDT response to the loads and to shrinkage should reflect the deformation in the concrete sample. Therefore, the grip-specimen interaction should not interfere with the measurement of deformation, and this depends on the instrumentation and how the LVDT is attached to the concrete specimen. Some experiments in the literature have the LVDT attached to the steel grips, a practice vulnerable to possible error due to the interaction between the grip and the concrete. This study considered two methods of attaching the LVDT. First, the LVDT is attached to the steel grips; second, the LVDT is attached to the concrete within the zone of reduced cross-section. The results indicate that attaching the LVDT to the grips results in errant measurement of the shrinkage stress, creep, and elastic strains due to the grip-specimen interaction. The consequences will be false interpretation of fully restrained shrinkage and creep characteristics because the grip-specimen interaction leads to a partially restrained test. The study suggests mounting the LVDT to the concrete sample away from the grips to achieve a fully restrained test. Results for two concrete mixtures with w/c ratio of 0.51 and 0.56 are discussed for both methods of attaching LVDTs.

Keywords: end effects; restrained shrinkage; shrinkage; tensile creep; tensile test

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INTRODUCTION

Early-age shrinkage and cracking of concrete has been a focal research in recent years due to the advent of high strength and high performance concrete with low water/binder (w/b) ratios, which are more prone to cracking. Early age shrinkage cracking is a key issue of long term durability and serviceability. Shrinkage of concrete is important because it is the main driving force for cracking, but the relaxation properties and the extent of restraint which will determine whether the shrinkage will lead to cracking are also important in the assessment of the consequences of shrinkage.

In view of the variety of factors that must be considered, quantitative cracking tests under restrained conditions are essential. Uniaxial restrained shrinkage tests have been developed and used in the literature to assess the early age shrinkage cracking (1-8). These tests can be divided into two main types according to the mode of restraint: passive restraint and active restraint. The passive restraint test fixes the end grips of the concrete sample by external rigid frame. The test used grips with tapered geometry to reduce stress concentration that may lead to premature cracking, and can be partially instrumented to measure the restraining force (1). The stresses developed in the passive test depend on the rigidity of the concrete and the restraining frame, and therefore the data obtained are not sufficiently fundamental. This shortcoming has been avoided in the development of the active restraint test. In the active test, one grip is fixed and the other is free to move. It is returned to its original position periodically, after some shrinkage has occurred. This is achieved by a special arrangement at the moving grip, whereby a screw or hydraulic mechanism is activated to bring the grip back to its original position, and a load cell measures the induced load. The active tests are either partially automated (3,4) or fully automated closed-loop systems (5,6). In both cases, the original position and the movement of the grip are either determined by a strain gage or by an LVDT.

A survey of the testing rigs indicated that the LVDT used to control the movement of the grip to maintain original length of the concrete sample is in most cases attached to the moving grip (e.g. 2,3,4,5). Consequently, the measured deformation may not exclusively reflect the shrinkage of the concrete sample between the grips because the LVDT measurement also incorporates whatever is happening within the grips. This could include the deformation associated with material damage or slip at the contact surfaces between the concrete and the grip. Consequently, a fully restrained test would be falsely assumed, and the data generated in these tests regarding shrinkage, creep and cracking would be erroneous if interpreted as for a fully restrained test. Recently, a fully closed-loop active restrained test has been developed at the University of Illinois (6,7), and the issue of the grip/specimen interaction has been investigated to ensure a fully restrained test. This paper sheds light on this important issue.

EXPERIMENTAL

Restrained Test Device

A fully automated restrained shrinkage test was developed to study the restrained shrinkage behavior and the relaxation properties for early age concrete [6,7]. The principle of the tests was based on the concept of Bloom and Bentur (4), which was integrated into a closed-loop system by Kovler (5). The developed system tests two identical "dog-bone" samples; one specimen is restrained and the load developed by drying shrinkage is measured, and the other specimen is unrestrained and the shrinkage deformation is measured. The dimensions of the specimen were selected to accommodate a maximum aggregate size of 25 mm. Each specimen is 1000 mm long and 76.2x76.2 mm in cross-section. The experiment is controlled by a closed loop system capable of highly accurate measurements and smooth loading.

A vertical layout of the experimental set-up was designed in which the test specimens were mounted vertically in a Universal Testing Machine. The bottom grip of the restrained specimen was fixed to the base of the machine, whereas the top grip was movable and was connected to the machine through a load cell. A swivel-joint was installed between the grip and the load cell to minimize eccentric loading. The free shrinkage specimen was vertically mounted on the base of the machine. The specimen cross-section is gradually enlarged to fit into the end grips. This design configuration minimizes stress concentration at contact surfaces. A general view of the experimental device is shown in Figure 1.

The restrained condition was simulated by maintaining the total deformation of the restrained sample within a threshold value of 5 μm, which is defined as the permissible change in the gage length of the specimen before restoration to the original length. The computer- controlled test checked shrinkage deformation continuously, and when the threshold was exceeded, an increase in tensile load was applied by the actuator to restore the concrete specimen to its original length. In this way, a restrained condition was achieved and the stress generated by shrinkage mechanism was measurable.

Comparison of the free shrinkage results with the shrinkage of the restrained specimen enabled discrimination of creep strain from shrinkage strain. Figure 2 shows how creep strain can be calculated from the restrained and free shrinkage test. The free shrinkage was measured from the free shrinkage specimen and the restrained shrinkage was based on the recovery cycles by which the specimen was loaded to restore its original length. Thus, each recovery cycle consisted of shrinkage and creep strain recovered by instantaneous elastic strain that was induced by incremental tensile load applied by the actuator. The sum of the elastic strain at any time is equal to the combined shrinkage and creep strains. Knowing the free shrinkage component, the creep strain can be quantified. The computer controlled recovery cycle in this test can be used to perform additional tests such as creep and relaxation, by programming the system to follow a different pattern. A variety of mechanical properties of concrete at early age such as components of strain, shrinkage stress, moduli of elasticity and creep coefficient can be determined by this experiment.

Instrumentation and LVDT Attachment

The longitudinal shrinkage was measured by a linear variable differential transformer (LVDT). Each measurement was an average value of 100 readings per second of the LVDT. Such a procedure permitted very high accuracy and reproducibility of linear displacement measurement of less than ± 0.1 μm.

Two ways of measuring the deformation were investigated. First, the LVDT was attached to the steel grips, and the gage length was the total length of the sample between the grips. In this case, the LVDT measures all deformations between the grips including the interaction at the contact surfaces. Second, the LVDT was attached to the concrete sample through a metal stud hooked to the concrete within the reduced cross-section. The gage length in this case is in the middle of the concrete sample away from the end grips. Several tests were performed for each configuration, and results from both methods will be presented and discussed. Schematic presentation of the LVDT attachment is shown in Figure 3.

Materials and Test Program

Two normal concrete mixtures with w/c ratio of 0.51 and 0.56 were tested under drying conditions. Materials used were Type I portland cement, crushed limestone aggregates with maximum size of 25 mm, and natural sand. The gradation of coarse and fine aggregates satisfied ASTM C33 requirements, and the fine aggregates had a fineness modulus of 2.2. The normal concrete mixtures had a paste volume fraction of 0.35. Proportions of the concrete mixtures are presented in Table 1.

Two series of tests were conducted for the two mixtures considered in this study. In the first series, the deformation measuring devices (LVDTs) were attached to the surface of the grips, while in the second series, the LVDTs were attached to the concrete samples a way from the end grips as shown in Figure 3. Several replicate tests were performed in each series.

In each test, two linear specimens were cast; one used for free shrinkage and the second for restrained shrinkage. Concrete specimens were cast, covered with plastic sheets and stored in a humidity chamber for 18 hours before installation in the machine. At this age, it was possible to handle the specimens and to instrument the test in the vertical layout of the experiment. Specimens were left unrestrained for 1-2 hours after exposure to minimize the effect of thermal shock that may cause premature failure as described by Kovler (9). The specimens were then exposed to drying at relative humidity (RH) of 50 %, and a temperature of 23 degrees C.

RESULTS AND DISCUSSIONS

Typical test results for the two ways of LVDT attachment are presented. The reproducibility of the test, shrinkage stress evolution, free shrinkage, tensile creep, creep coefficient, elastic modulus, and stress-elastic strain are presented. The effect of the method of LVDT attachment in the reliability and accuracy of the data generated from the test is also discussed.

To evaluate reproducibility of the experiment, replicate tests were performed for both methods of attachments. Figures 4 and 5 present the stress development of replicate tests when the LVDTs were attached to the grip surface and to the concrete, respectively. Clearly, both methods generated reproducible data and both methods seemed reliable for such a test. However, the magnitude of the stress developed for each method differed for the same concrete mixture as shown in Figure 6. This suggested that the two methods represented different restraint conditions. Further analysis of the data of the free shrinkage, creep and stress-strain helped address this issue.

The free shrinkage strain measured from the free shrinkage specimen is shown in Figure 7 for the two methods of LVDT attachment. The results indicate that the free shrinkage is similar for both methods, which suggests that the stress development should not differ. But the fact that the stress development was different created concern about the degree of restraint and the grip-specimen interaction. The interaction between the grip and the specimen and its effect on the degree of restraint will exist only if there is a load applied to the grips as in the case of restrained test. Therefore, similar free shrinkage strain measurements are expected, and the results indicated a reasonable consistency and similarity between the two methods.

From the measured load and the strain recovered on each recovery cycle of the restrained test, a stress – elastic strain can be established. The stress is calculated from the cumulative loads measured in the restrained specimen, and the strain is cumulative strain obtained from the compensation cycles. The stress-strain relation obtained for the two methods is shown in Figures 8 and 9 for the two concrete mixtures tested in this study. It is clear that the calculated stress when the LVDT is attached to the steel grips is much lower than when the LVDT is attached to the concrete. Despite the lower stresses however, the calculated strain "presumably elastic strain" is much higher, which cannot be true for the same concrete.

The LVDT attachment method also affects measurement of the elastic modulus. The calculated secant modulus is presented in Figure 10 for the concrete mixture with w/c ratio of 0.56. The calculated values of the secant modulus when the LVDT was attached to the grips did not agree with literature values at this age. The concrete (w/c = 0.56) was expected to reach a modulus of elasticity of about 20 MPa after 24 hours, however the calculated values from the test results ranged between 8 and 12 MPa. The attachment of the LVDT on the steel grips resulted in errant measurement of the elastic strain due to grip-specimen interaction whereby part of the strain recovered in the compensation cycle was recovered in the form of slip and not as elastic strain in the concrete. As a result, the specimen was partially restrained and a false low value of elastic modulus was obtained.

When the LVDT was attached to the concrete, the shrinkage stress measured in the experiment was higher as shown in Figures 6, 8 and 9, which indicated a fully restrained condition. Furthermore, the calculated modulus of elasticity was in reasonable agreement with normal values for concrete.

Interpretation of the Interaction

Past studies that used LVDTs mounted on the grips typically considered the gage length of the specimen to be the free length of concrete in between the grips (e.g. Figure 3 shows the free length as 673 mm). However, the concrete volume within the gripped ends is also subject to stress. In fact, the state of stress within the gripped ends is very complex with some regions in compression and other regions in tension. The concrete volume within the gripped ends certainly undergoes elastic and creep deformation, and contributes to the overall measured deformation if the LVDTs are mounted on the grips. Furthermore, there is potential for slip to occur between the grips and the concrete. Since such tests assume that the gage length is the free length between the grips, the measured deformation is always higher than the true value for the assumed gage length. The excess deformation is evident in Figures 8 and 9, and the magnitude of the excess deformation increases as tensile load increases.

If the LVDTs are mounted on the grips, the specimen would behave as one that is not fully restrained. The shrinkage stresses in the test would reflect a partially restrained condition, and the time of first cracking would be delayed. The resolved creep strain would not accurately reflect the true relaxation properties because creep depends on the level of stress which would be higher in the fully restrained case. Figure 11 shows the creep coefficient for the two methods of measurement, and the creep coefficient was underestimated when the LVDTs were mounted to the grips. The excess deformation would be falsely interpreted as elastic strain in the concrete, and will lead to an underestimated modulus of elasticity as shown in Figure 10.

This study has shown that the error associated with mounting the LVDTs on the grips is of a significant magnitude. While there may be little impact in measurement of free shrinkage, the error will affect all properties that depend on the restrained specimen measurements. In such a case the relaxation properties and cracking of concrete characterized by this test would falsely overestimate performance of the concrete in the field.

SUMMARY AND CONCLUSIONS

The interaction between the end grips and the concrete samples in dog-bone-shaped uniaxial restrained tests is substantial. The common practice of mounting LVDTs on the steel grips for measuring specimen length change is a procedure that introduces error if fully restrained conditions are desired. Tests use cross-head measurements may not also be appropriate. When the LVDT is attached to the grips, excess deformation is included in the measurement. The excess deformation is due to elastic and creep strains in the concrete volume located within the grip ends, and slip between the grips and the concrete material. The excess deformation becomes more critical in active closed-loop restrained shrinkage tests where the LVDT signal is the controlling parameter. The consequences will be false interpretation of fully restrained shrinkage and creep characteristics because the grip-specimen interaction leads to a partially