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Predicting the tensile creep of concrete

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Abstract

Over a four year period, six phases of testing were performed to observe the influence of age at loading, applied stress level, mix composition and relative humidity on the tensile creep of concrete. From these investigations it was possible to develop a model which allowed the prediction of tensile creep based on a knowledge of the compressive strength of the concrete (determined at the age of loading), the applied stress level and the relative humidity. Subsequently, this model was validated using the results from three independent investigations. Compressive creep as well as tensile creep was also obtained. This allowed a comparison of compressive creep with tensile creep and illustrated that on the basis of equal stresses, tensile creep is on average between 2 and 3 times greater than compressive creep (the maximum ratio is in excess of 8). For this investigation, however, on the basis of stress / strength ratio the difference between tensile and compressive creep is less significant. Considering a simply supported flexural reinforced concrete element, the investigation suggests that it is unwise to consider actual compressive creep equal to actual tensile creep as is often the case in design practice.

Keywords: tensile creep, modelling, basic and drying creep, tensile and compressive creep ratios, loss of tension stiffening

Introduction

Creep potentially enhances the long-term deflection of reinforced concrete members by way of two mechanisms. Firstly, the combination of compressive and tensile creep, independent of shrinkage, will effect a change in the slope of the strain profile and hence increase curvature with time [1]. Of course, this increase in curvature is influenced by the symmetry of the reinforcement (top and bottom steel) and the inherent restraint offered by the steel to the imposed movement, and the ratio of tensile to compressive creep which is not unity but has been shown to be as high as 10 in unreinforced concrete [2].

Secondly, the deflection of a beam or slab is influenced by the tension stiffening capacity of the composite section. Tension stiffening is a measure of the concrete which is active in resisting the tensile forces generated in bending; it is present in the regions between the primary cracks. According to Beeby and Scott [3] the stiffening effect of the concrete in the tension zone reduces by up to 50% after approximately 20 days; the stiffening effect then remains constant for a constantly applied load. From a practical perspective, this may be misleading as it is very rare that loading on any structure is constant. Loading will vary, possibly repeating at some irregular frequency about the design load (i.e. above and below) which will therefore lead to further loss of tension stiffening [4]. On the other hand, it is very rare that a stabilised crack pattern is achieved in many statically designed structures and so tension stiffening will in all likelihood initially be higher than the 50% level proposed by Beeby and Scott.

With respect to the tension stiffening phenomenon, one of the mechanisms of loss of stiffness is internal cracking which occurs between the primary cracks, within the cover, radiating out from around the bar. This internal cracking reduces the composite behaviour between the concrete and the steel reinforcement and hence the effective stiffness and, according to Beeby and Scott is partly due to tensile creep. This is reasonable as the controlling mechanism of tensile creep is microcracking and it is not unreasonable to expect this deterioration process to enhance this internal cracking and hence promote further deflection [2]. Tensile creep is a long-term phenomenon and although perhaps (depending on age, environment etc) it is definitely more rapid at early ages (less than 50 days) its continuation in the long-term can, as such reasonably be expected to produce a continued degradation of tension stiffening; in fact, it has recently be shown that it is not constant with time after approximately 20 days as Beeby and Scott claim [2, 4].

Whilst tensile creep can have a negative effect on the behaviour of a structure it can also act positively, in that it can relieve induced stresses caused by the restraint of imposed strains (early thermal movement, shrinkage). These internal stresses result from for example, the internal restraint offered by the steel reinforcement and they can, depending on the symmetry of the reinforcement affect the curvature of a beam / slab. The extent of this shrinkage curvature is also dependent on the degree of tensile creep and the ratio of tensile to compressive creep.

It is, therefore, clear that a knowledge of tensile creep and the ability to predict the degree of tensile creep is important. There are several established methods for predicting the compressive creep of concrete [5-7]. However, their suitability for tensile creep prediction is in question as the mechanisms of compressive and tensile creep are different. Several integrated theories [8-19] have been proposed for the mechanism of compressive creep; in these theories, creep is ascribed to more than one of the following mechanisms: mechanical deformation theories, plastic theories, viscous and visco-elastic flow theories, delayed elasticity, seepage theory, microcracking, activation energy theory, solidification theory and microprestress-solidification theory. However, for tensile creep the more popular consensus, as mentioned earlier, is that its mechanism is dominated by microcracking.

This paper attempts to develop a method of predicting the tensile creep of unreinforced concrete. It considers the influences of age at loading, mix composition, stress level, normal / high strength concrete, cement mortars and relative humidity. The ultimate values are obtained by the extrapolation of short term data using the Ross Hyperbola [20] and the log relationship proposed by Neville and Brooks [21]. The model developed in this investigation is then validated using data obtained on normal strength concrete (Kristiawan [22], Li et al [23]) and high performance concrete (HPC) [2]. The creep measured from these unreinforced prisms / cylinders and bobbins are unlikely to occur in reinforced concrete design elements where, for instance, movements are restrained by the steel and where different stress states exist. This restraint offered by the steel is still to be accurately determined. However, the ratio of tensile to compressive creep at low stresses derived from this investigation will further help with the fundamental understanding of the effect of creep on deflections.

Experimental details

In all cases tensile creep was measured on concrete bobbins using the test set-up shown in Figure 1. Tests were performed in a controlled environment room under conditions of 60% relative humidity (RH) +/- 5% and 20 °C +/- 0.5. For the basic creep tests, a RH of 100 % was achieved by sealing the respective specimens. Curing of all specimens was performed in a fog room at 99% RH and 20 °C; samples were stored in the fog-room until the tests began in the controlled environment room (there was therefore no pre-drying of samples). Compressive creep was obtained from both prism and cylinder samples in the usual way [24] (see Figure 2) and account was made for any minor differences in drying path lengths by using the volume / surface (v/s) ratio when any comparisons were drawn. (In accordance with the method developed by Neville [24], once the stress is applied to the samples, a constant average stress (+/- 5%) is maintained by regularly adjusting the loading nuts. Initially, the frequency of adjustment is 3 or 4 times a day; this frequency reduces to once every day after approximately 2 weeks.)

Figure 1 Tensile creep rig (with Bobbin under load)

Figure 2 Compressive creep rigs (showing unsealed and sealed concrete prisms)

The analysis is based on a collation of several MSc experimental investigations. Initially, tensile creep was investigated in order to try and explain the additional long-term moments that develop in monolithically (indeterminate) reinforced concrete (rc) joints both in situ and in the laboratory, and to explain the effect tensile creep has on the loss of tension stiffening. Subsequent investigations looked at the effect of mix composition and cement replacements in concrete and aggregate replacements in cement mortars (using recycled material). High strength concrete was also monitored. The initial driver for this work was not therefore to develop a prediction model for tensile creep and there are, therefore, some potential shortcomings of the model. For instance, with respect to strength of concrete and mix composition, it will be seen that the model developed attempts to represent variations in mix composition by requiring the compressive strength of the concrete at the age it is loaded as input data for the model. As such, it is limited as it cannot in its current form predict the creep based on cement content per se (similar for instance to established models [5-7]). However, such an elaborate model may not necessarily be required for the prediction of tensile creep; the model in its proposed form can still be considered practical. It must also be noted that the extrapolated ultimate values are often based on short-term data (less than 50 days of loading) and this in itself may reduce the accuracy of the model. However, incorporating data from cement mortars in the development of the model could arguably be beneficial as, depending on the accuracy of the model, further evidence confirming the effect of the coarse aggregate on the tensile creep of concrete could be provided.

Results and Observations

Test series 1 (variables: age, stress level)

For test series 1, the creep of concrete loaded at 3 different ages (3, 7 and 28 days) was monitored. In addition, 3 levels of stress (0.5, 1.0 and 2.0 MPa) were investigated. Table 1 illustrates the mix composition of the concrete; the mix incorporated 40% cement replacement with Ground Granulated Blast Furnace Slag (GGBS); a water-cement ratio of 0.5 was chosen. As mentioned above, the mix was an ‘industry’ mix and actually duplicated the design of a concrete which was used in the construction of a partially buried water retaining structure with monolithic roof to wall joints. This structure is still currently being monitored to assess its long-term performance under differential thermal loading.

Table 1: Test series 1 – material specification and mix composition

Figures 3 to 5 illustrate the compressive and tensile creep of the concrete loaded at 3, 7 and 28 days, respectively. Each figure also illustrates the effect of stress level on the creep of the concrete. The 3, 7 and 28-day compressive strengths were 25.17, 37.63 and 53.70MPa, respectively. The corresponding tensile strengths (on this occasion only obtained from the split cylinder test) were 2.27, 2.56 and 3.76MPa, respectively.

Figure 3: Creep of samples loaded at 3 days

Figure 4: Creep of samples loaded at 7 days

Figure 5 Creep of samples loaded at 28 days

As expected [25] at these low stress levels, the relationship between compressive creep and applied stress is inconsistent, although it is clear that the amount of creep does increase with increasing applied stress and there is some degree of proportionality for the samples loaded at 28 days. Interestingly, although these results appear to confirm that compressive creep at low stresses is greater than that which would be expected from samples subjected to a load of between 20 and 60% of the compressive strength at age of loading there does appear to be some degree of proportionality at the lower stresses (less than or equal to 1MPa). As the stress level becomes greater (i.e. 2MPa) the specific creep reduces below that which was actually measured at a stress of 1MPa and as mentioned above, confirms the findings of Powers [25] who cited higher specific creep at lower stresses (due to disjoining pressures between particle surfaces). It therefore appears that at a level of stress of 2MPa, sufficient compressive stress is produced within the system to press together the surfaces of the crystallised silicates allowing the formation of new bonds between the surfaces and reducing overall subsequent creep. For this investigation, no linear relationship between applied stress and tensile creep was apparent; as with compressive creep, tensile creep increased with increasing applied stress.

Test series 2 (variable: mix design)

For this series, the effect on creep of w/c ratio and two different types of washed ash as filler replacement were investigated. Table 2 details the mix compositions for the different samples tested. As it can be seen, this series was different to the other 5 series of tests in that only cement mortar samples were considered and not concrete samples. These samples were actually part of a much broader investigation into the use of waste ashes as replacement materials in concrete; these ashes in their raw form are currently not suitable for inclusion in concrete however they do appear to work in their treated form.

The two types of washed ash (designated WASH I and II) were used for partial volumetric replacement of the fine aggregates. The first type of ash (WASH I) was obtained from the hoppers of the heat recovery system of a municipal solid waste incinerator (MSWi) while the second type (WASH II) was obtained as a mixture of "WASH I", semi-dry scrubber ash and fabric filter ash from the same MSWi. The washed ash replacement of fine aggregates was set at 10% and 20% of the volume of sand for two variations of water-cement ratio (0.45 and 0.65).

All specimens were cured in the fog room and loaded at 28 days. A constant stress of 1MPa was used for the tensile creep tests; a compressive stress of 20% of the 28-day strength was used for the compressive creep tests (between 6.2MPa and 10.3MPa – see Table 2). For the samples with w/c ratio of 0.65, data for MIX 1 (tensile) have not been included – the sample failed during assembly of the test. Also, the MIX 5 (compressive) data were excluded as the wrong calibration data was used for the load cell.

Table 2: Test series 2 – mortar mix compositions

Figures 6 and 7 illustrate the compressive and tensile creep of mixes 1, 3 and 5 (w/c = 0.65) and mixes 2, 4 and 6 (w/c = 0.45), respectively. Each figure also shows the effect of stress level on the creep of the concrete.

Figure 6 Creep of samples with a w/c ratio 0.65

Figure 7 Creep of samples with a w/c ratio 0.45

Observing the compressive creep, there appears to be no influence on creep when 10% of the fine aggregates were replaced with WASH II. This observation applies for each w/c ratio. Mix 6 (20% WASH I replacement) did exhibit more compressive creep. It was expected that the replacement aggregates would have some influence on the measured creep because of the greater water absorption property of the replacement aggregates (i.e. the water absorption of the sand was equal to 0.55% whereas the water absorption of WASH I and II was 10.8% and 19.6%, respectively). Although a direct comparison cannot be drawn between Mix 4 and Mix 6 because of the different replacement ashes used in each mix, it appears that the effect of the higher water absorption property of the replacement ashes only materialises once the replacement levels exceed 10%. The increased creep of Mix 6 does also correlate with the reduction in strength recorded for these two mixes (see Table 2).

Again, no direct comparisons can be made on the effect of the replacement ashes on tensile creep, although the influence of the ash type and quantity does seem to be more apparent. However, the effect of w/c ratio does appear to be more apparent with Mix 6 (w/c = 0.45) exhibiting a lot less tensile creep than Mix 5 (w/c = 0.65). The difference is, in fact, in-line with the relationship suggested by Lorman [25] i.e. that creep is approximately equal to the square of the water / cement ratio. Certainly from the direct tensile strength values obtained for the 6 mixes, the WASH replacements have much less influence on the direct tensile strength than w/c ratio (i.e., Mix 4 – 2.26MPa vs Mix 6 – 2.09MPa: Mix 5 - 1.32MPa vs Mix 6 – 2.09MPa).

Comparing the levels of compressive creep of the mixes with a w/c ratio of 0.45 from this test phase (mortars) with that recorded in Test Series 1 (concrete – w/c ratio = 0.5) for samples loaded at 28 days, it can be seen that the creep of the mortar samples is around twice that of the concrete samples in Test Series 1. There is clearly an indication of the restraint effect of coarse aggregate on creep in compression. However, in terms of the tensile creep, a comparison of this test phase data with the tensile creep of Test phase 1 shows that the tensile creep of the concrete (Series 1) is of the order of 2 to 3 times the tensile creep recorded in the mortars. The presence of coarse aggregate will lead to the formation of an interfacial transition zone (ITZ) around the coarse aggregate. These regions are known to be populated with microcracks [27] and, under tension, the presence of these microcracks will enhance tensile creep. The results also possibly indicate that any restraint offered by the coarse aggregate when samples are loaded in tension is actually minimal.

Series 3 (variables; mix composition and stress level)

For test series 3 the creep of concrete specimens made using two different mixes and subjected to three different levels of tensile and compressive stress (0.25, 0.75 and 1.25 MPa) was investigated. Ground granulated blast-furnace slag (GGBS) was used to replace 50% of the total cement content of MIX I and 70% of the total cement content of MIX II. All the specimens were loaded at 7 days. A multi-functional super plasticizer called Viscocrete 10 (GB) was added, in different proportions, as a water reducing admixture to the two concrete mixes; this was to improve the workability of the wet concrete without compromising the required water-cement ratio.

Details of the material compositions of the two different mixes are presented in Table 3 below.

Table 3: - Test series 3 – material compositions of Mix 1 and Mix 2

Figures 8 and 9 illustrate the effect of 50% (Mix 1) and 70% (Mix 2) GGBS content, respectively on tensile and compressive creep. Again it can be seen that although creep can be related to stress level, neither tensile nor compressive creep were proportional to stress level at these low stress levels. The 28-day compressive strengths for Mix 1 and 2 were 48.42 and 57.95MPa, respectively. The corresponding direct tensile strengths were 2.71 and 3.51MPa, respectively.

Figure 8 Creep of MIXI samples containing 50% GGBS

Figure 9 Creep of MIXII samples containing 70% GGBS

It is difficult to draw any further relationships from these results. Each mix contains a similar w/c ratio and each mix exhibits similar tensile and compressive creep. Previously, it has been shown that by increasing the GGBS content (the degree of cement replacement), the level of creep reduces [23]. However, as mentioned earlier, in order to preserve a similar w/c ratio for the two mixes, over 300% more SP was used in Mix 2. According to Brooks [29], admixture concrete such as this should on the whole exhibit more creep but the increase is not that significant, particularly under drying conditions; again the influence of admixtures is similar to the effect that GGBS has on strength development. The influence of GGBS content and SP is further complicated by the fact that the stress / strength ratio of Mix 1 is almost 50% greater than that of Mix 2 (the 7-day compressive strengths of Mix 1 and 2 are 32.75MPa and 46.23MPa, respectively). Overall, it might be expected therefore that Mix 1 would exhibit more compressive creep than Mix 2 although it may also be expected that the difference in creep between the two mixes would have been greater due to the difference in stress / strength ratio. This suggests that the SP may be more significant than initially thought.

The direct tensile strengths of Mix 1 and 2 at 7 days were 2.55MPa and 3.28MPa, respectively. Although similar levels of creep were recorded for a stress of 0.25MPa, there is a slight reduction in the tensile creep of Mix 2 at 0.75MPa and 1.25MPa when compared to the tensile creep of Mix 1. Similar to the compressive creep discussed above, the increase in creep in Mix 1 reflects the fact that the stress / strength ratio of Mix 1 is approximately 20% greater than that of Mix 2, and the influence of GGBS cement replacement (also witnessed by Li et al [23]).

Series 4 (age, stress level)

For test series 4 the creep of high strength concrete (HSC) specimens, at two different ages of loading (3 and 7 days) and subjected to three different levels of tensile and compressive stress (0.5, 1.0 and 2.0 MPa), was investigated. The concrete specimens were grouped into two separate batches; the first batch (Batch 1) was cured for 3 days after casting and then loaded while the second batch (Batch 2) was cured for 7 days after casting before being loaded. A super plasticizer called Sika ViscoCrete 25 MP was added to the concrete mix and ground granulated blast-furnace slag (GGBS) was used to replace 40% of the total weight of the cement required. A water-cement ratio of 0.52 was used. The 28-day strengths were 93.91MPa (compressive) and 5.25MPa (direct tensile).

Details of material specification and mix composition are presented in Table 4 below.

Table 4: Test series 4 – materials specification and mix compositions

Figures 10 and 11 illustrate the creep of HSC loaded at 3 and 7 days, respectively. As before, the figures suggest no real proportionality between applied stress and creep. As expected, on the whole creep tends to reduce with increasing age at loading; the effect of age appears to be more significant on compressive creep. Strengths (compression / direct tension) at 3 and 7 days were 65.86MPa / 3.84MPa and 73.56MPa / 4.29MPa, respectively.

Figure 10 Creep of samples loaded at 3 days

Figure 11 Creep of samples loaded at 7 days

Series 5 and 6 (variables: age, stress level and relative humidity (RH))

For test series 5 and 6 the basic (100% RH) and drying creep behaviour of concrete specimens loaded at two different ages (9 and 28 days) was studied. The concrete specimens were grouped into two separate phases; in the first phase (Phase 1), the concrete specimens were cured for 28 days after casting and then subjected to sustained loading for a period of 115 days while in the second phase (Phase 2), the concrete specimens were cured for 9 days after casting and subjected to sustained loading for a period of 70 days.

For series 5, in the first phase, the concrete specimens were subjected to three different levels of compressive stress (1.0, 2.0 and 8.0 MPa) and two levels of tensile stress (1.0 and 2.0 MPa) while in the second phase, the specimens were subjected to three levels of compressive stress (1.0, 2.0 and 5.0 MPa) and only one level of tensile stress (1.0 MPa). Ground granulated blast-furnace slag (GGBS) was used to replace 40% of the total weight of the cement required and a water-binder ratio of 0.62 was used for all specimens in both Phases 1 and 2.

For series 6, in the first phase, the concrete specimens were subjected to two levels of compressive stress (1.0 and 8.0 MPa) and one level of tensile stress (1.0 MPa), while in the second phase, the specimens were subjected to one level of compressive stress (1.0 MPa) and one level of tensile stress (1.0 MPa). To prevent exchange of moisture between the basic creep specimens and the external environment, the basic creep specimens were wrapped immediately after de-moulding using a water-proofing material.

Details of material specification and mix composition for the samples of series 5 and 6 are presented in Table 5 below.

Table 5: Test series 5 and 6 – material specifications and mix compositions

Figures 12 and 13 illustrate the results of the series 5 tests; the results of the series 6 tests are shown in Figures 14 and 15.

Figure 12 Phase 1 – creep of samples loaded at 28 days

Figure 13 Phase 2 – creep of samples loaded at 9 days

Immediately apparent from Figs 12 and 13 was the significant influence of age on the tensile creep of the concrete – this had previously not been so obvious. The 28-day direct tensile strength of the first phase concrete was 2.6MPa whereas the 9-day strength for the Phase 2 concrete was 2.06MPa. Even accounting for the greater stress / strength ratio applied in Phase 2, the tensile creep is significantly higher. However, comparing the tensile creep of this concrete measured at 9 days with that measured at an age of loading of 7 days from Series 3 (50% GGBS) it can be seen that, taking into account theoretical influences of age, w/c ratio and stress/ strength ratio, the tensile creep of the Phase 2 concrete of series 5 looks reasonable. It is recommended that the low level of tensile creep recorded in Phase 1 is treated cautiously, especially if this data is compared with the HSC results presented in Series 4 which also contains 40%GGBS, has a lower w/c ratio and stress / strength ratio and yet exhibits almost 50% more tensile creep.

Figure 14 Phase 1 – creep of samples loaded at 28 days

Figure 15 Phase 2 - creep of samples loaded at 9 days

Observing the tensile creep of Series 6 (Figs 14 and 15) there does appear to be a slight influence of age on basic creep (100% RH) – creep measured at 9 days was slightly greater than that measured from 28 days. This is not in agreement with Illston [28] who reported little reduction in basic tensile creep with age which he explained was due to the slow increase in tensile strength of concrete with age. For this investigation, the increase in tensile strength from 9 to 28 days was 26%, which is not insignificant. In comparison, the influence of age is far more significant on drying tensile creep. The level of basic creep is higher than that recorded by other investigators [22, 23]. However, the direct tensile strength of the concrete recorded at the time of loading, i.e. 2.06MPa at 9 days and 2.6MPa at 28 days is reasonably low; as such, a stress / strength ratio of between approximately 40 to 50% was applied which is a lot greater than the 20% ratio applied in the other investigations, although still within the 20 to 60% limit of proportionality between stress / strength ratio and measured creep. Basic tensile creep is less than drying tensile creep. This was expected and is in agreement with many other researchers, i.e. Domone [29], Brooks [30], Rossi et al [31]. They cite that for drying creep, the movement of water to the outside of the sample is essential, something not possible under basic conditions, and that this effect is greater than the basic creep that occurs from the internal movement of water (into empty pores, particularly gel water into stressed regions between particles [32]) which takes place in sealed concrete. Domone [29] further states that this lower tensile creep in sealed specimens is due to a lower moisture content within the actual paste which is a result of self-dessication brought about by autogenous shrinkage. Also, this phenomenon is enhanced by microcracking [31, 33-35].

Discussion and Analysis

As mentioned previously, there were a number of drivers for these series of tests and these drivers initially took preference over the development of a model to predict ultimate tensile creep in concrete. In many of the test series it was not possible to relate tensile creep behaviour to one influence alone and several factors have acted concomitantly. Whilst age at loading, applied stress level (and subsequently stress / strength level) and relative humidity were more easily identifiable variables and as such easier to be able to comment on with respect to their effect on creep, the mix composition (i.e. cement replacement, additives, aggregate type) effects were not isolated well enough and could potentially have jeopardised the subsequent development of a model. However, it was found that by relating the tensile creep to the compressive strength of the mixes at their age of loading, mix composition was reasonably well considered for the mix designs investigated in these investigations. The benefit of using the compressive strength parameter is that it is an easy and convenient property to measure, much more convenient than the direct tensile strength.

Figure 16 plots the compressive strengths measured during these 6 investigations against the direct tensile strength recorded at the same age. The relationship appears to be best represented by a linear function (Equation (1) which can be forced through zero, although this reduces the coefficient of determination (R^2) to 0.8429.

$$y = 0.0584x \tag{1}$$

where y represents direct tensile strength and x represents compressive strength.

Figure 16 Plot of Direct Tensile Strength against Compressive Strength

The compressive and direct tensile strength data of these investigations was also used to assess the accuracy of the guidance provided in Eurocode 2 (Table 3.1) [36] on the prediction of direct tensile strengths. These predictions are presented in Figure 17 where it can also be seen that the Eurocode consistently over-predicts the direct tensile strengths measured in these investigations (compare with Fig 16 (actual values)). This can be explained by the fact that the Eurocode prediction is based on cylinder strengths whilst the strengths recorded in these investigations are from cube samples.

Figure 17 Predicting the tensile strength of concrete from the measured compressive strength using Eurocode 2

Bearing in mind that the initial aim was not to develop a prediction model for tensile creep, the short-term data presented above was used to estimate the ultimate creep. As mentioned previously, this was achieved by extrapolating the data using the Ross hyperbolic function [20]. The data presented in Table 6 represents the ultimate values estimated using the Ross formula.

Table 6: Summary of Ultimate Tensile Creep values

The data presented in Table 6, in conjunction with the values for compressive strength quoted earlier, were then used to develop Figure 18, which plots ultimate tensile creep against compressive strength for all stress levels. (Figure 18 actually depicts a regular grid of points connecting the ultimate tensile creep against the compressive strength. The regular spaced values (more than the data shown in Table 6) are interpolated based on a least square second order polynomial fitting. The link between the age at loading and the compressive strength is provided throughout the manuscript.)

Figure 18: Relationship between ultimate tensile creep and compressive strength for different applied stresses

The similarity in the trend of the curves for each of the stress levels suggests that this data set is suitable to be represented by a single relationship whereby the tensile creep can be predicted from a knowledge of the compressive strength and the applied stress. This relationship was developed using MATLAB [37] and is as follows:

$$f(x, y) = -1377 - 425.3x + 30.21y + 3.593xy - 0.1921y^2 \qquad (2)$$

Figure 19 illustrates the polynomial fitted to the data (Equation 2), where f(x, y) represents the Ultimate Tensile Creep ($R^2 = 0.997$); and x = Stress Level (MPa) and y = Compressive Strength (MPa). (Note: The choice of a second order polynomial was made to preserve the simplicity of the proposed prediction formula while still producing a good fit. The standard least square option of MATLAB's curve fitting toolbox (i.e. cftool) was employed for this task.) At this point, it is possible to predict the tensile creep of concrete using the concrete strength at the required age of loading (between 3 and 28 days). Of course, if only the 28-day compressive strength of a concrete is known an assessment of the strength at the actual age of loading (if less than 28 days) can be made using the guidance available in Eurocode 2 [36].

Figure 19 Two plots showing the accuracy of the predicted square - polynomial to the experimental data

Subsequently, an attempt was made to validate this relationship using drying tensile creep obtained by Ahmed [2] and Kristiawan [22]. Typically, the ultimate specific tensile creep estimated from Ahmed's research (the 28-day compressive strength of the HSC at the age of loading was 99.26MPa) was 410 microstrain; the predicted specific creep from Equation (2) is 343 microstrain, an under-prediction of 16% and acceptably within the ± 20% prediction error normally cited for creep and shrinkage predictions. (Ahmed's mix contained 15% silica fume and 0.87% superplasticiser; the w/b ratio was 0.28.)

Kristiawan only reports drying specific tensile creep data up to 7 days, as such the extrapolated ultimate creep must be treated cautiously. Again, interpreting the data and using the Ross hyperbolic function the ultimate creep is predicted to be around 350 microstrain. Using an average compressive strength of 51MPa to represent his 6 different mix types, the predicted tensile creep using Equation (2) is 568 microstrain, which is a 62% over-prediction and as such is significantly outside accepted prediction tolerances.

Ignoring potential errors that may be incurred from extrapolating using 7-day data, there may be two factors that have influenced this over-prediction. Firstly, this over-prediction may in some way be due to the 14 day direct tensile strengths measured by Kristiawan. The average tensile strength for the 6 mixes was 3.20MPa, however, using his compressive strengths in Equation (1) above to predict tensile strengths gives an average tensile strength of 2.8MPa. This difference in strengths is a good indication that the creep measured by Kristiawan would be less than that predicted from this investigation (based on a simple comparison of stress / strength ratios). In order to account for this influence a revised, conservative figure for the tensile creep measured by Kristiawan is proposed of 400 microstrain, still a 40% over-prediction.

Secondly, and perhaps more influentially is the fact that Kristiawan performed his tests at 65% ± 5% RH whereas, on the whole, the RH used for these 6 test series reported here was between 55 and 60%. From the data collected in Series 6 on ultimate creep measured at 100% RH (i.e. basic tensile creep) it is possible to make some assessment of the effect of RH on tensile creep by incorporating this data in the form of a further factor into the prediction equation (Equation (2) presented above). Troxell et al [38] state that the relation between creep and relative humidity is linear (for similar times under load). From Table 6, the average of specific tensile creep collected under drying and basic conditions in Series 6 for samples loaded at 9 and 28 days can be calculated (i.e. 338μs); Equation (2) can then be modified to represent the effect of relative humidity conditions of between 100% and 60% on tensile creep as follows:-

$$f(x, y) = -1377 + [(RH - 60)(338/40)] - 425.3x + 30.21y + 3.593xy - 0.1921y^2 \qquad (3)$$

Assuming a RH of 70% for the 7 days that the samples were under load in Kristiawan's tests, the ultimate tensile creep predicted by Equation (3) would be 493 microstrain, which is only a 23% over-prediction.

Li et al also investigated the early age tensile creep of a number of blended cement concretes. Their investigation was also performed under environmental drying conditions of 65 ± 5% RH, however, the control temperature was 30 ± 2 °C. The samples were loaded at an age of 3 days and subjected to a stress of 30% of the 3-day strength. Based on the mix compositions, it is likely that strength gain will increase faster at later ages and so their samples were potentially subjected to a low stress / strength ratio and expected to produce lower values of creep. Based on the higher humidity and low stress / strength ratio a low overall creep would be expected compared to that measured in this investigation. Although, the effect of the slightly higher temperature will act to enhance creep; this effect is expected to be greater for the samples from which basic creep was obtained [39]. No actual strengths were provided by the authors so a further validation of the prediction formula could not be achieved (although effect of temperature could not be considered), however, the levels of tensile creep reported were of the same order to that which could be reasonably predicted by Equation (3) and the ratio of basic to drying tensile creep reported is in-line with that seen in this investigation and predicted by the model (even allowing for the influence of temperature).

Ratio of tensile to compressive creep

There is sufficient evidence to suggest that the ratio of tensile to compressive creep is not unity but that tensile creep is greater than compressive creep. However, this is dependent on the basis on which the ratio is defined. The ratio can be derived using creep measured at equal stresses, in which case tensile creep can be up to several times greater than compressive creep. However, this approach may underestimate the ratio, as to measure creep at equal stresses the applied maximum stress must be limited to potentially 2MPa because of the tensile strength of the concrete in tension; more appropriately 1MPa stress is used. This is approximately 20 to 40% of the tensile strength which is within the range where creep is supposed to be linearly proportional to applied stress. However, such stresses are considered to be very low for compressive creep tests (potentially less than 5% of the compressive strength of the concrete) and outside the accepted range of proportionality between applied stress and measured creep. At such low levels of stress, creep is not proportional to applied stress; the amount of compressive creep is much greater than the relationship would suggest. For instance, by comparing the compressive creep of concrete at 1, 5 and 8 MPa measured in this investigation, the non-linearity of creep with applied stress is clearly apparent. At 28 days, the compressive creep at 8MPa is 860 microstrain; specific creep would therefore be estimated at 108 microstrain (860 microstrain / 8MPa) from these results and creep at 2MPa would be estimated at 215 microstrain (860 microstrain / 4MPa). However, measured creep at 1 and 2MPa was 370 and 500 microstrain, respectively. Similar non-linear behaviour can be seen by referring to Figs 13-15. Hence, hypothetically if the tensile and compressive creep could be measured at equal stresses where the stress level is approximately 10% or more of the compressive strength of the concrete, compressive creep would be reduced and the ratio would be increased. Of course this is not possible as higher applied stresses would cause instantaneous failure of the tensile specimens or at least some form of tertiary creep which would lead to failure. Hence, a ratio derived from creep at equal stresses is indicative of the difference between tensile and compressive creep but it may not be truly definitive.

Another basis on which the creep in tension and compression can be compared is the applied stress / strength ratio. On the basis of equal stresses the stress / strength ratio for the tensile creep tests performed in this investigation is typically 0.25 to 0.6. However, for the compressive creep tests the stress / strength ratios were less than 0.1 (and in some cases as low as 0.02). For equal stress / strength ratios, the applied stress would have to increase for the compression tests and whilst this increase cannot be accurately quantified from the results of this investigation (due to the apparent non-linearity described above) it is reasonable to suggest that the compressive creep will increase such that the ratio of tensile to compressive creep will be more similar to unity and perhaps even less than 1.

In practice, when considering a cracked flexural reinforced concrete spanning element, the applied stress in the concrete compression and tension zone is not the same. Typically, at Serviceability Limit State (SLS), the maximum average stress in the compression zone is around 5 to 16MPa for normal strength concrete depending on the degree of cracking and / or the ratio of applied moment to cracking moment (and assuming an elastic stress distribution across the compression zone); the maximum stress in the tension zone is around 3 MPa (in the concrete between the cracks) and on average will be around 1MPa. Test phases 5 and 6 considered the compressive creep at stresses of 1, 5 and 8 MPa (where the 5 and 8 MPa also represented 20% of the compressive strength of the concrete at 9 and 28 days, respectively) and the tensile creep at stresses of 1MPa, in order to compare the creep measured at applied stresses equivalent to those seen in practice. It is possible therefore that when considering one, the potential stresses that can occur in rc elements in practice and two, the levels of tension and compression creep seen in this investigation that similar applied stress / strength ratios can occur in the tension and compression zones of a beam / slab and that on the basis of stress / strength ratio it is reasonable to assume that actual compression creep is equivalent to actual tensile creep at SLS. However, the likelihood of this happening consistently is not very high. On the occasion where actual compressive creep does equal actual tensile creep in the sections of the rc elements between cracks, curvature will change due to this creep but the neutral axis position will not change unless the reinforcement is unsymmetrical. In such a case, the restraint to movement will be greater where the area of steel reinforcement is greater (normally where the tension steel is located) and this will reduce the creep in the tension zone and lead to a drop in the position of the neutral axis. However, there is sufficient evidence to suggest that the probability of similar stress / strength ratios occurring in the compression and tension zone is low. Therefore, the fact that the actual tensile creep is not equal to the actual compressive creep means that this inequality should be considered in any assessment of neutral axis position / change in curvature and in a re-examination of the loss of tension stiffening with time.

Conclusions

From a consideration of age at loading, stress level, and compressive strength (used in part as a representation of the mix compositions investigated in this series of tests) it does appear possible to reasonably accurately predict the ultimate tensile creep of unreinforced concrete (at least to within approximately ± 20%). The validation performed and reported here is not conclusive for all factors but sufficient evidence is provided to suggest that this approach is therefore reasonable. Of particular interest is the approach of using compressive strength as an indicator for mix composition. This needs further investigation, as intuitively whilst perhaps fitting with a range of mixes it should not be representative of all mix types (for instance mixes containing shrinkage reducing agents); the accuracy and applicability of this approach can be further improved. However, the level of accuracy of such a prediction method to ultimately assist with such practical applications as the estimation of deflection in rc spanning elements is yet to be determined; it may be that the accuracy already exhibited by this first version of the model is sufficient.

The lack of effect that the absence of coarse aggregate has on tensile creep is interesting yet not unsurprising, i.e. the role of the aggregate in promoting microcracking is potentially less influential than its physical restraint which is negated under tensile stress. Encouragingly, or perhaps specific to this work, even with such short durations of loading, the accuracy of the model seems unaffected. However, this needs investigating further and tests over longer periods are required.

As has been shown before, tensile creep is clearly affected by age at loading (at least up to 28 days) and whilst related to stress level it is not proportional to applied stress. As has also been seen before, this non-linearity at these levels of stress also applies to compressive creep. As with compressive creep, tensile creep also appears to be related to RH however more data are required throughout the range of possible relative humidities to confirm whether tensile creep is linearly related with RH. Confirmation of the relationship between RH and tensile creep may be a future required refinement to the proposed model (as it could be seen earlier that RH clearly had an effect on the accuracy of the model).

For completeness the compressive creep for each mix has also been presented. In doing so, an estimation of the range of the tensile to compressive creep ratio can be calculated. As has been shown by other researchers, at these low stress levels, when the stress in compression is equal to the stress in tension, compressive creep is not equal to tensile creep. On average, considering all mixes from the 6 series of tests, the ratio of tensile to compressive creep is 2.4. The highest ratio is 8.91; the higher values tend to be produced by the more mature concrete at low stresses. This is reasonable as the stress / strength ratio in compression will be lower in comparison to similar criteria for tension specimens. Two values of unity were recorded.

The levels of applied stress in the tension and compression zone of flexural rc elements are different. By considering this difference in applied stress in the two zones; the compressive and tensile strength of the concrete and the levels of tensile and compressive creep determined in this investigation, it can be seen that it is possible for the actual compressive creep to be equal to the actual tensile creep (and similar stress / strength ratios to exist in tension and compression). However, there is sufficient evidence to suggest that the probability of similar stress / strength ratios occurring in the compression and tension zone is low. Therefore, the fact that the actual tensile creep is not equal to the actual compressive creep means that this inequality should be considered in any assessment of neutral axis position / change in curvature and in a re-examination of the loss of tension stiffening with time.

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Table 1: Test series 1 – material specification and mix composition

Material Specifications		
Description	C28/35 MCC300 (Max. W/C=0.5)	
Maximum aggregate size	20 (mm)	
Cement type	CIIIA+SR	
Targeted Slump	70-100 (mm)	
Mix composition		
Type	Source	Dry batch weight (kg/m^3)
CEM I	CEMEX-South Ferriby	198
GGBS	CEMEX-Appleby Scunthorpe	132
10mm Limestone	CEMEX-Dove Holes	1155
0/4 Sand replacement	CEMEX-Dove Holes	375
0/1 Fine sand	WBB-Cove Farm	385
Water	Free water-cement ratio	0.5

Table 2: Test series 2 – mortar mix compositions

Mortar mix	***Applied Compressive Stress (MPa)***	***Mass of constituents (kg)***			
		Sand	**Ash**	**CEM I 42.5R**	**Water**
MIX 1	7.56	*Control mix (w/c ratio = 0.65)*			
		17.550	-	5.247	3.410
MIX 2	9.80	*Control mix (w/c ratio = 0.45)*			
		17.550	-	6.610	2.975
MIX 3	7.62	*10% WASH II replacement (w/c ratio = 0.65)*			
		15.795	1.695	5.247	3.410
MIX 4	10.34	*10% WASH II replacement (w/c ratio = 0.45)*			
		15.795	1.695	6.610	2.975
MIX 5	6.20	*20% WASH I replacement (w/c ratio = 0.65)*			
		14.040	3.483	5.247	3.410
MIX 6	9.52	*20% WASH I replacement (w/c ratio = 0.45)*			
		14.040	3.483	6.610	2.975

Table 3: - Test series 3 – material compositions of Mix 1 and Mix 2

Material	Dry batch weight (Kg/m^3)	
	MIX I	***MIX II***
Portland cement	170	120
GGBS	170	280
Coarse aggregate	1160	945
Fine aggregate	710	815
Water	166	182
Super plasticizer	0.8	3.0
Water-cement ratio	0.49	0.46

Table 4: Test series 4 – materials specification and mix compositions

Material	Dry batch weight (kg/m^3)	Percentage by weight (%)
Ordinary Portland cement (Type I)	295	11.8
GGBS	200	8.0
Microsilica	80	3.2
Fine aggregate	525	20.9
Coarse aggregate (10 mm)	375	15.0
Coarse aggregate (20 mm)	865	34.5
Water	155	6.2
Super plasticizer	11.7	0.5
Water-cement ratio	0.52	

Table 5: Test series 5 and 6 – material specifications and mix compositions

Material	Dry batch weight (kg/m^3)
Ordinary Portland cement (Type I)	198
GGBS	132
Fine aggregate	736
Coarse aggregate	1104
Water	205

Table 6: Summary of Ultimate Tensile Creep values

Series 1

Age at Loading	0.5MPa	1.0MPa	2.0MPa	
3 days	934	1110	1451	
7 days	785	925	1277	
28 days	434	583	804	

Series 2

w/c ratio	MIX 2	MIX 4	MIX6	
0.45	85	121	177	
	MIX1	MIX 3	MIX 5	
0.65	-	176	357	

Series 3

MIX	0.25MPa	0.75MPa	1.25MPa	
Mix I	522	726	804	
Mix II	447	619	693	

Series 4

Age at Loading	0.5MPa	1.0MPa	2.0MPa	
3 days	318	439	598	
7 days	252	377	506	

Series 5

Age at Loading	1.0MPa	2.0MPa		
28 days	354	667		
9 days	928	-		

Series 6

Age at Loading	Basic (1.0MPa)	Drying (1MPa)		
28 days	364	692		
9 days	647	995		

Figure 1 Tensile creep rig (with Bobbin under load)

Figure 2 Compressive creep rigs (showing unsealed and sealed concrete prisms)

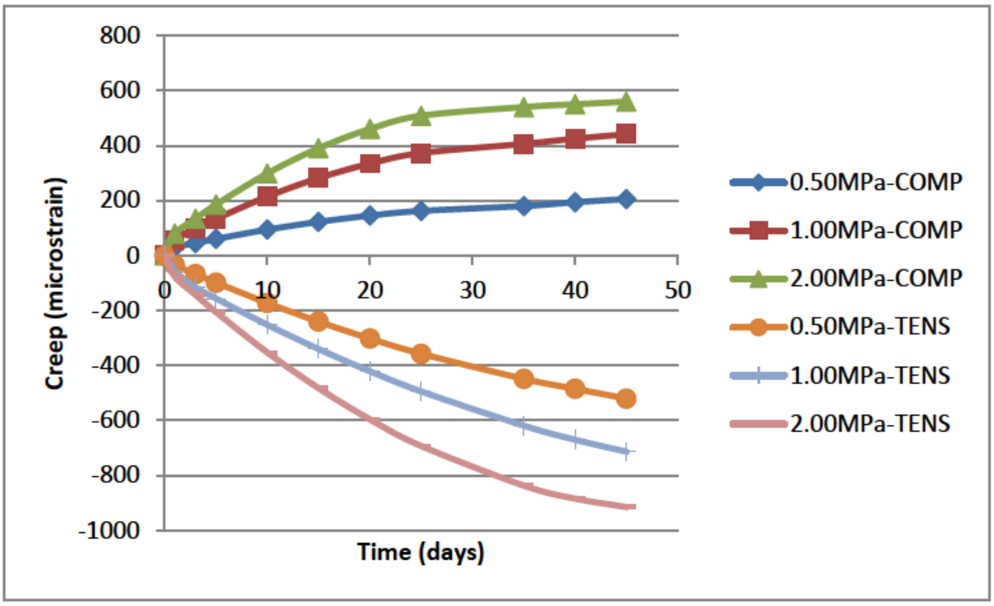

Figure 3: Creep of samples loaded at 3 days

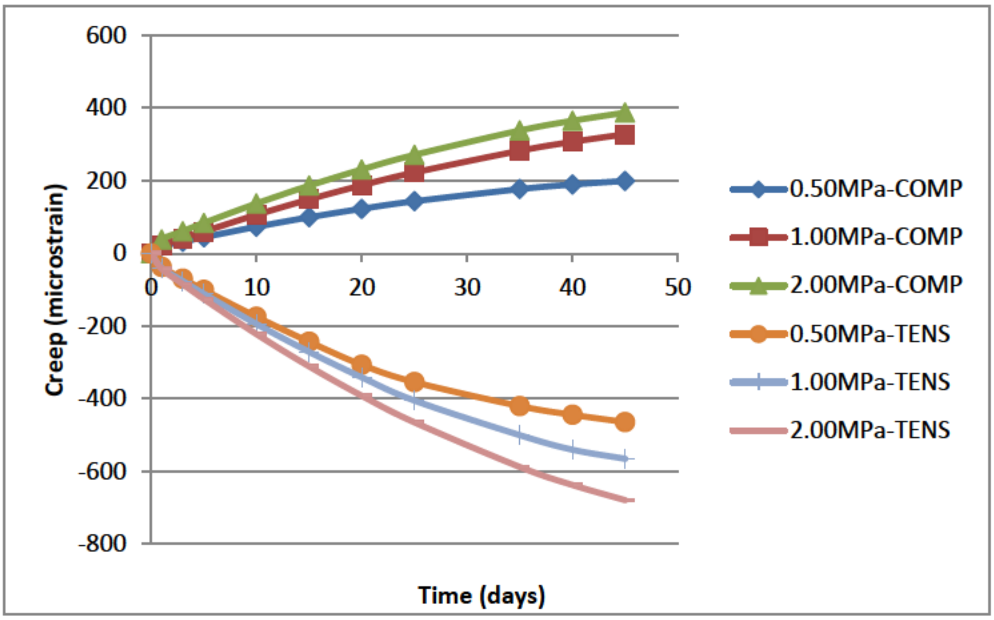

Figure 4: Creep of samples loaded at 7 days

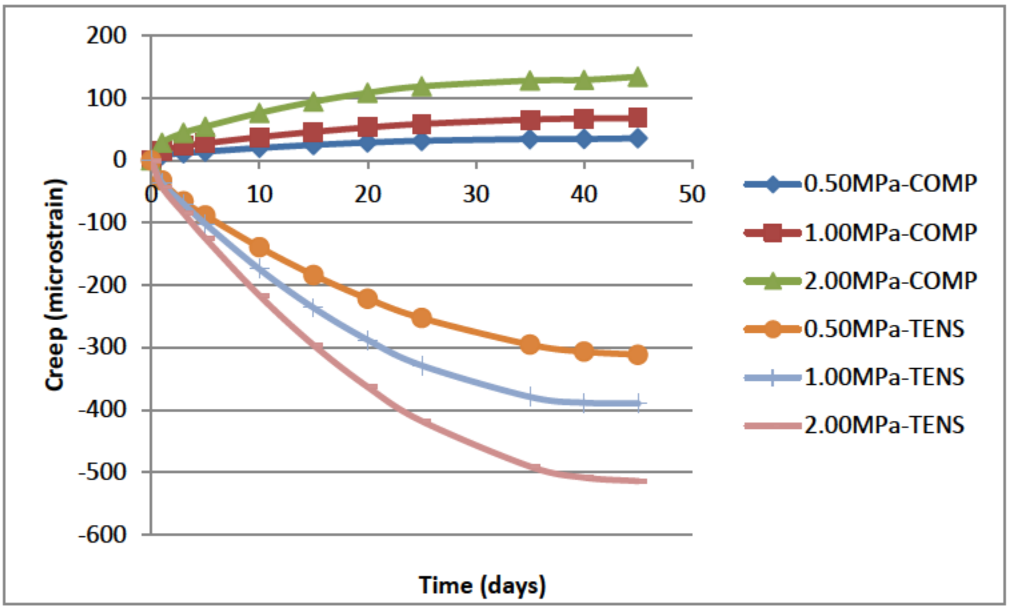

Figure 5 Creep of samples loaded at 28 days

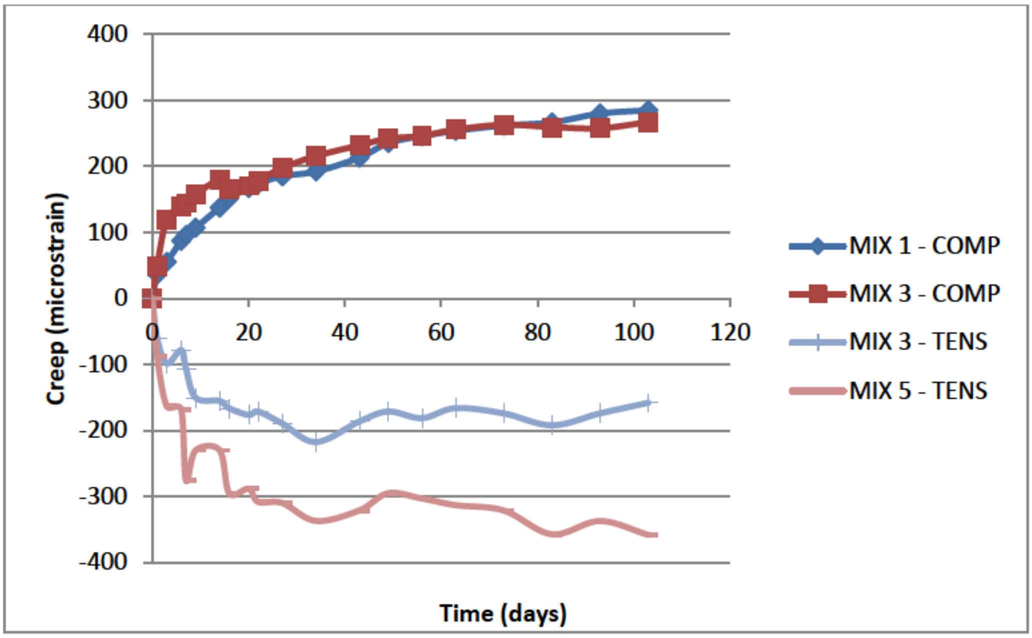

Figure 6 Creep of samples with a w/c ratio 0.65

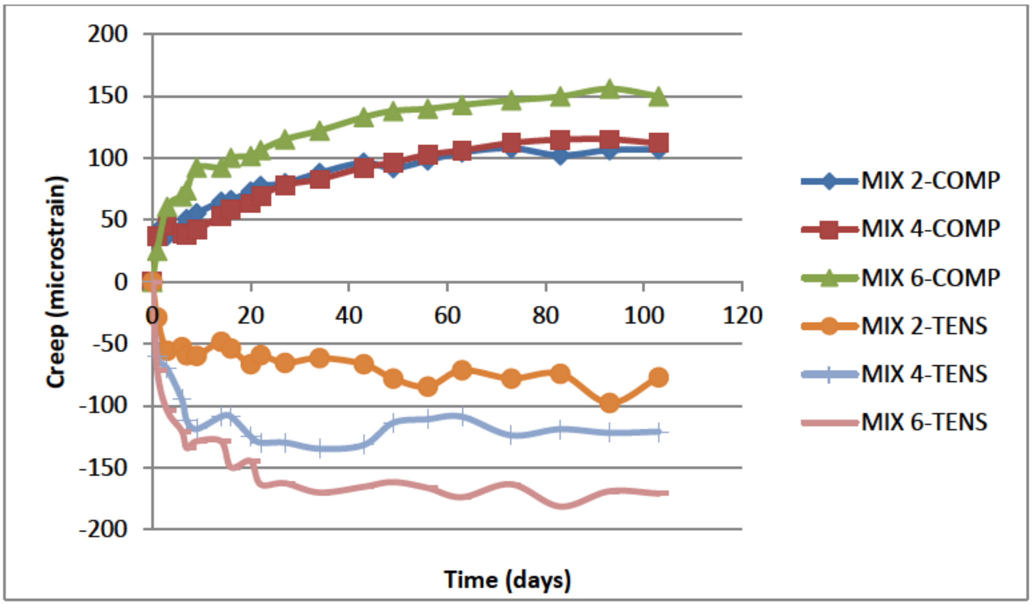

Figure 7 Creep of samples with a w/c ratio 0.45

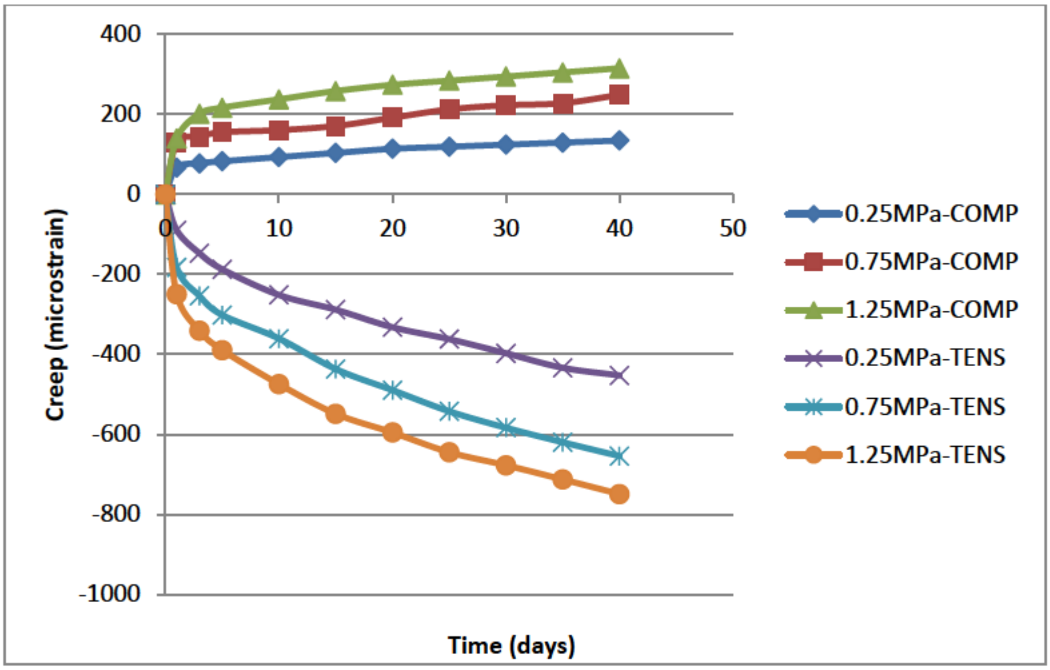

Figure 8 Creep of MIXI samples containing 50% GGBS

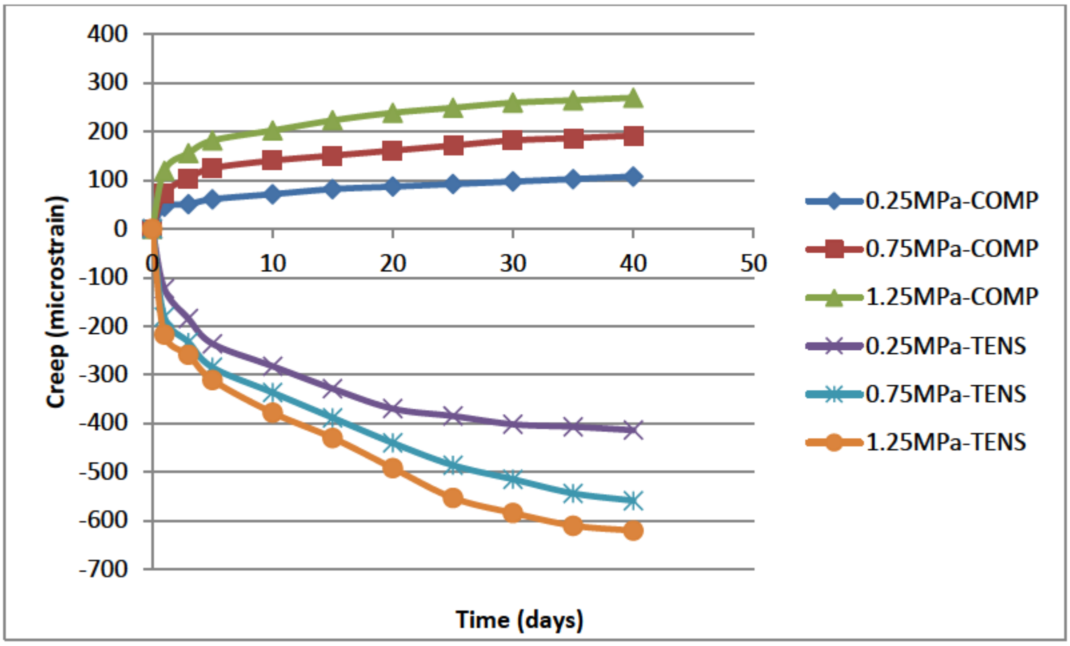

Figure 9 Creep of MIXII samples containing 70% GGBS

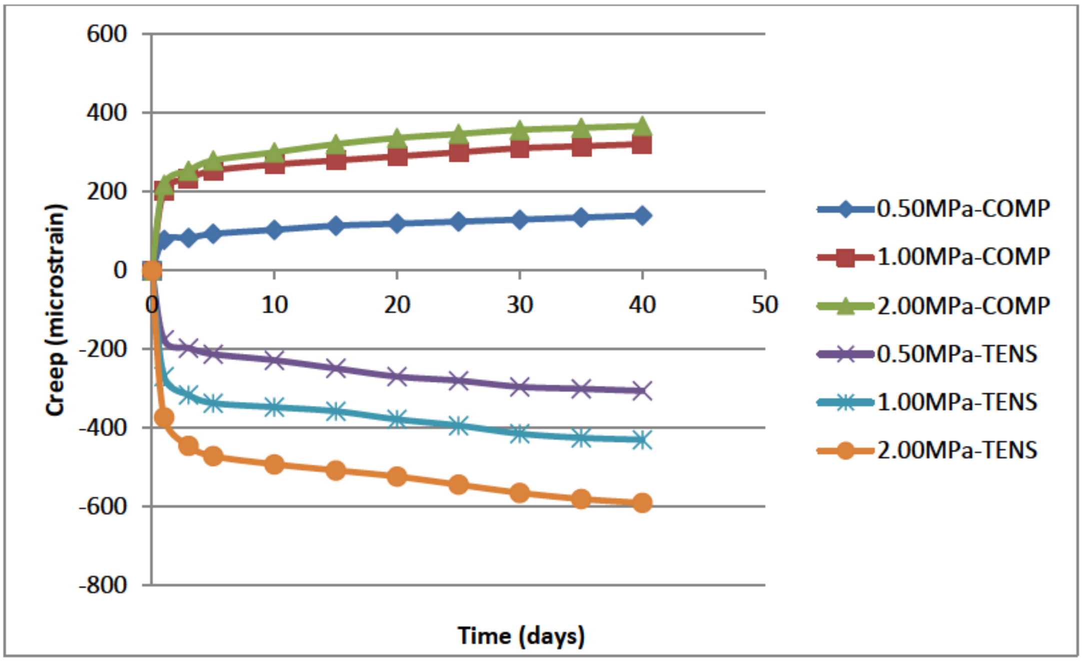

Figure 10 Creep of samples loaded at 3 days

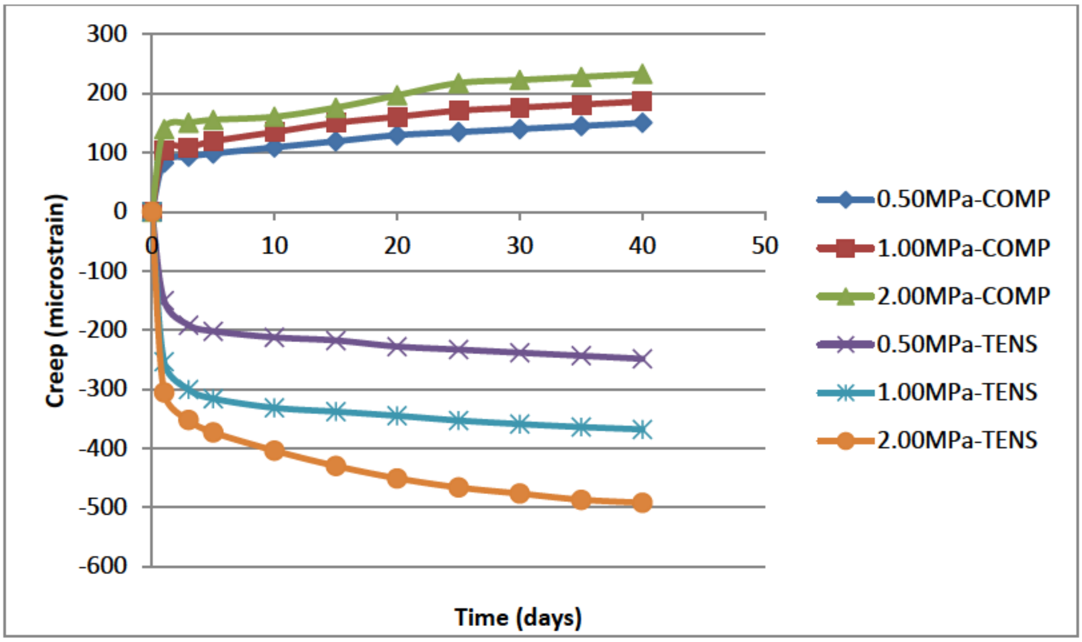

Figure 11 Creep of samples loaded at 7 days

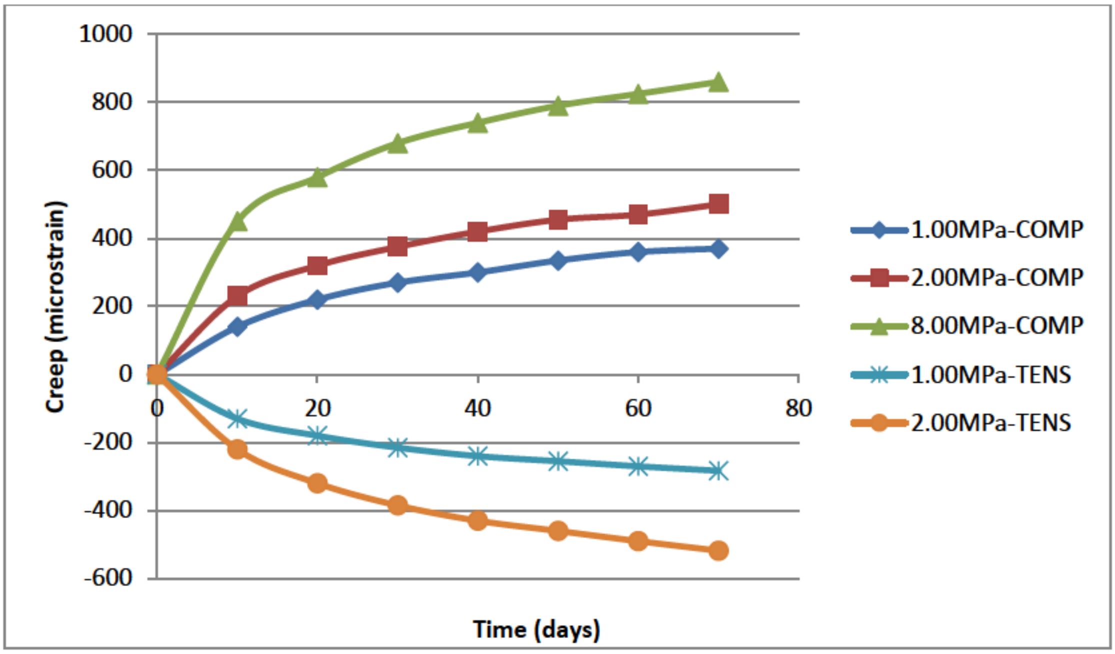

Figure 12 Phase 1 – creep of samples loaded at 28 days

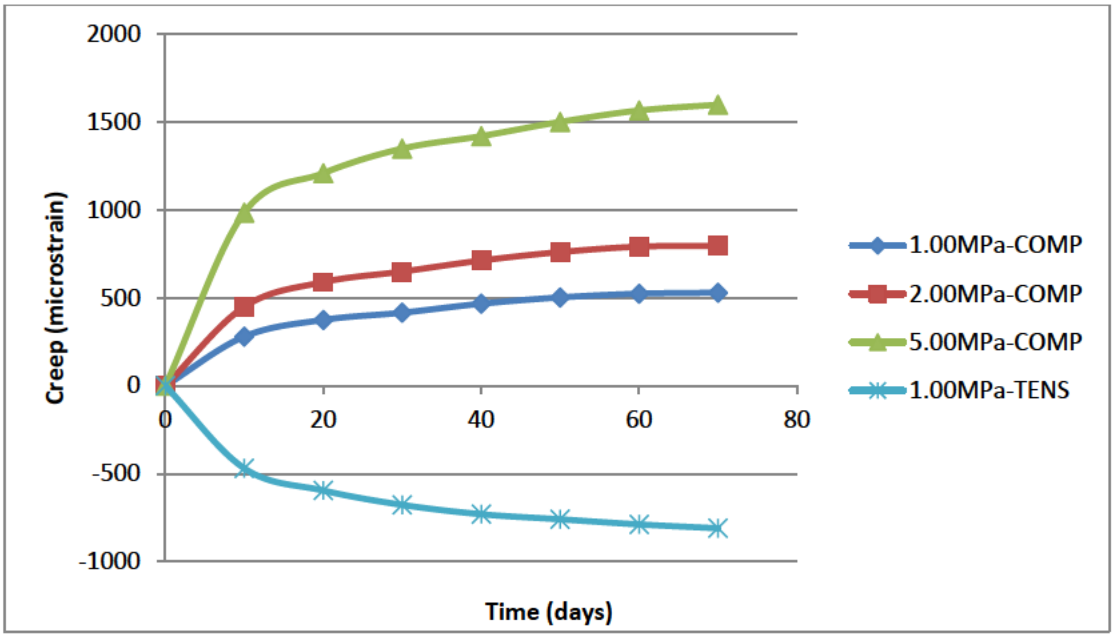

Figure 13 Phase 2 – creep of samples loaded at 9 days

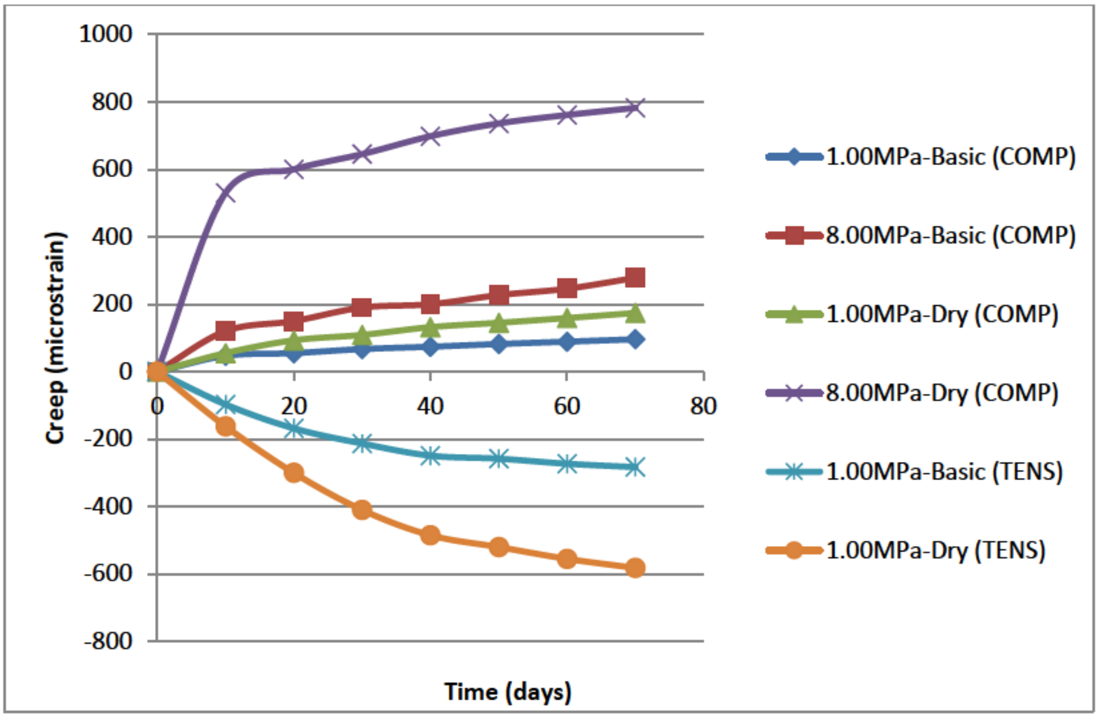

Figure 14 Phase 1 – creep of samples loaded at 28 days

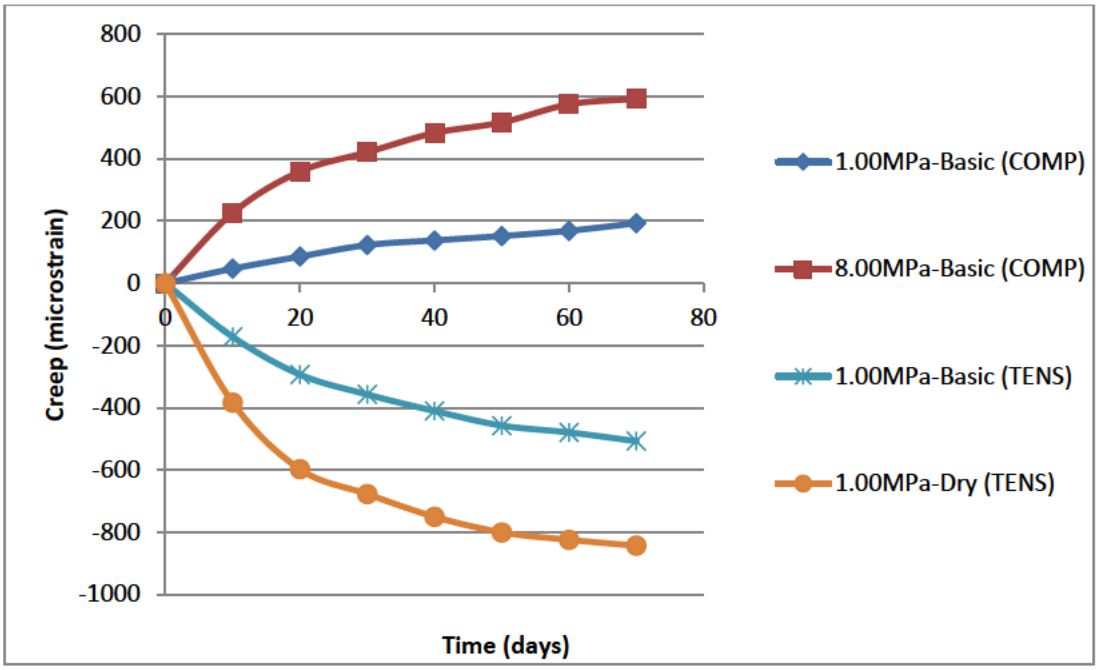

Figure 15 Phase 2 - creep of samples loaded at 9 days

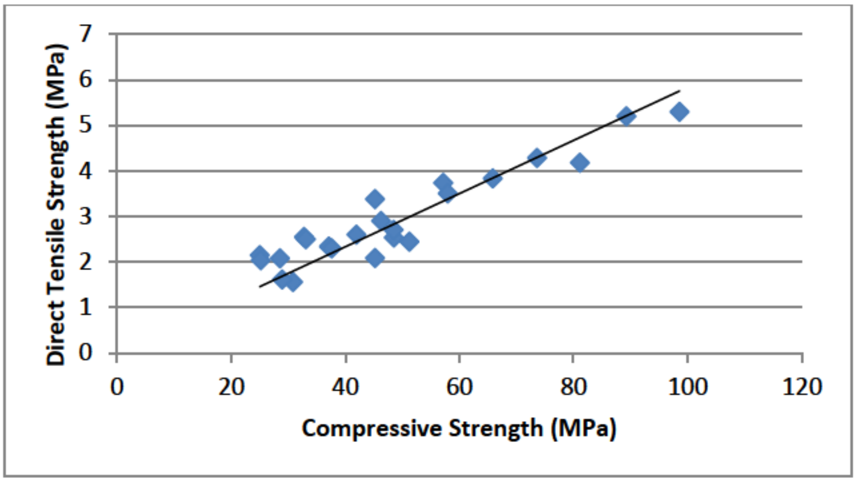

Figure 16 Plot of Direct Tensile Strength against Compressive Strength

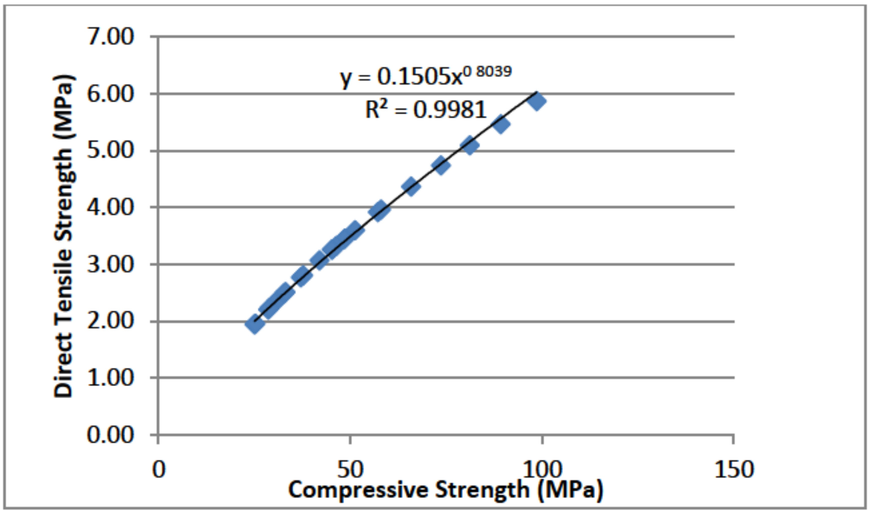

Figure 17 Predicting the tensile strength of concrete from the measured compressive strength using Eurocode 2

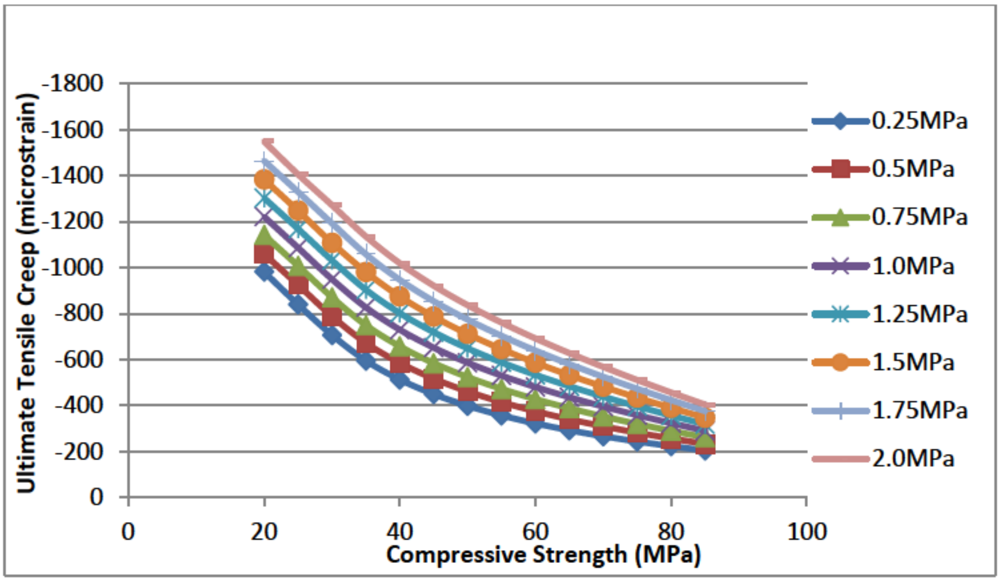

Figure 18: Relationship between ultimate tensile creep and compressive strength for different applied stresses

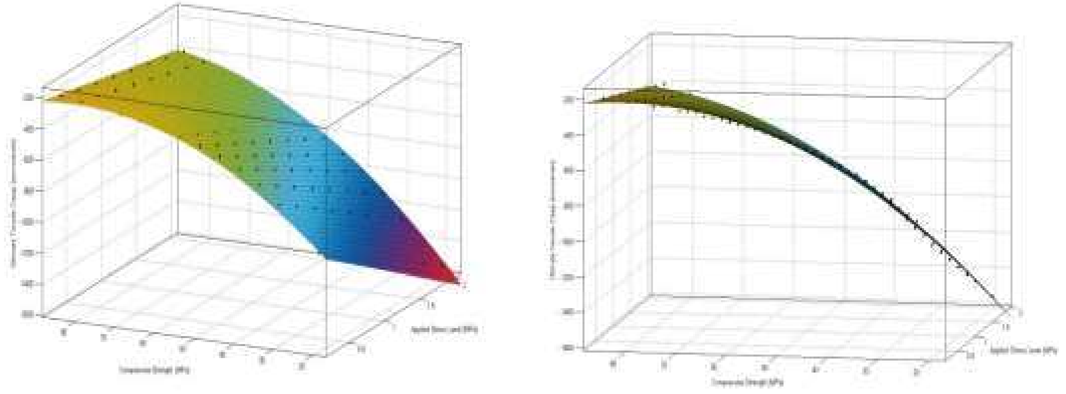

Figure 19 Two plots showing the accuracy of the predicted square - polynomial to the experimental data