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The Influence of Aggregate Stiffness on the Creep of Concrete

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ABSTRACT: Creep is the time-dependent increase in strain of a solid body under sustained stress. In concrete, the negative effects of creep are often responsible for excessive deflection at service loads which can result in cracking, creep buckling of long columns and loss of prestressing force.

While it is conceptually easy to appreciate that the stiffness of the aggregate in concrete will influence the magnitude of creep, the extent of this effect across the range of commonly-used aggregates in South Africa has not been assessed. This paper discusses the results of an investigation that was aimed at quantifying the influence of aggregate stiffness on the measured creep behaviour of plain concrete. The experimental programme included measurements of total creep on concrete specimens of two different strength grades for each of the three commonly-used South African aggregate types (quartzite, granite and andesite). In addition, elastic modulus tests were conducted on cores of the aggregate types assessed.

The test results revealed that no clear correlation exists between the creep of concrete and the stiffness of the included aggregate. These results appear to be attributable to the more dominant effect of other influencing factors such as stress-strain behaviour of the aggregate/paste interfacial zone, particularly in the case of aggregates with elastic moduli in excess of 70 GPa.

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The influence of aggregate stiffness on the creep of concrete

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While it is conceptually easy to appreciate that the stiffness of the aggregate in concrete will influence the magnitude of creep, the extent of this effect across the range of commonly used aggregates in South Africa has not been assessed. This paper discusses the results of an investigation that was aimed at quantifying the influence of aggregate stiffness on the measured creep behaviour of plain concrete.

The experimental programme included measurements of total creep on concrete specimens of two different strength grades for each of three different but commonly used South African aggregate types (quartzite, granite and andesite). In addition, elastic modulus tests were conducted on cores of the aggregate types assessed.

The test results revealed that no clear correlation exists between the creep of concrete and the stiffness of the included aggregate. These results appear to be attributable to the more dominant effect of other influencing factors such as the stress-strain behaviour of the aggregate/paste interfacial zone, particularly in the case of aggregates with elastic moduli in excess of 70 GPa.

Introduction

Creep is the time dependent increase in strain of a solid body under sustained stress. In concrete, the source of creep lies in the cement paste and the magnitude of creep is influenced by a wide range of variables. Some of these variables relate to the intrinsic properties of the concrete mixture while others are associated with extrinsic environmental factors. The intrinsic factors include aspects such as water : cement ratio, degree of hydration, age of the cement paste, cement type, moisture content, member geometry and size, aggregate content and aggregate properties. The extrinsic factors include applied stress, duration of load, age at first loading, load history, relative humidity, temperature and rate and time of drying.

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In this context, the role of the aggregate is to reduce the extent of creep deformation in two fundamental ways: firstly by displacing some of the volume of the cement paste and secondly, by providing physical restraint against the deformation of the cement paste. This is true provided the aggregate is itself dimensionally stable. In its role as a physical restraint, it is conceptually easy to appreciate that the stiffness (or elastic modulus) of the aggregate would have a strong effect on the magnitude of concrete creep.

Separate research projects undertaken by Davis and Alexander (1992), The Concrete Society (1974), Soroka and Jaegermann (1972), Rusch et al., (1962) and Troxell et al., (1958) showed the aggregate type to have an influence on the creep of the concrete in which it is embedded. However, it is difficult to find definitive opinion in this work on the influence of the stiffness of the aggregate on the magnitude of creep deformation.

The work by Davis and Alexander (1992) considered eight of the most commonly used South African aggregate types, from 23 sources throughout the country. The results of this investigation led to the establishment of empirical "Relative Creep" values, ranging from approximately 0.7 to 1.5, for the different aggregate types. This important work showed that it was possible to cause a more than doubling of the creep deformation in concrete by simply changing the geological type of the aggregate. However, the work did not definitively separate the influence of the aggregate stiffness from other possible properties related to the aggregate type.

The purpose of the investigation reported here was to determine the influence of aggregate type and stiffness on the creep behaviour of plain concrete for up to six months under load. The specific objectives of this research were to:

- Determine the correlation between total creep of concrete and the elastic modulus of the aggregate used in the concrete;
- Assess the differences in the specific total creep behaviour of concretes of two different w/c ratios each containing one of three different commonly used South African aggregate types. The aggregate types considered were quartzite from the Ferro Quarry in Pretoria, Granite from the Jukskei Quarry in Midrand and Andesite from the Eikenhof Quarry in Johannesburg, South Africa;
- Compare the findings to those of Davis and Alexander (1992) who conducted research on the total creep of concretes containing quartzite or granite or andesite from the same sources as those used in this research.

Experimental Details

Materials

A single batch of CEM I 42,5 cement from the Dudfield factory of Alpha Cement was used for all the tests carried out in this investigation. Quartzite (Q) from the Ferro quarry in Pretoria, granite (G) from the Jukskei quarry in Midrand and andesite (A) from the Eikenhof quarry in Johannesburg were used as both the stone and sand aggregates for the concrete. The stone was 19mm nominal size and the fine aggregate was crusher sand.

Two rock boulders were collected from each of the quartzite (Ferro) and andesite (Eikenhof) quarries for the determination of the elastic modulus of the rock. Since the rocks observed in the Granite (Jukskei) quarry appeared quite variable, two boulders with visually different characteristics were collected from this quarry. All these boulders were obtained from the same areas in the respective quarries where rock material was obtained to produce the aggregates used to make the concrete samples for this investigation.

Laboratory Procedures

Determination of elastic moduli of the aggregates

Measurements of aggregate elastic modulus or stiffness were carried out on samples obtained from the representative boulders collected as described above. The stiffness of each rock type as determined on the boulder samples was taken to be representative of the stiffness of the corresponding aggregates used in the concrete specimens.

Three cores measuring 42mm in diameter and 82mm long were cut from each set of two boulders and these were tested according to the procedure described in BS 1881 (1983) to determine the elastic modulus of the aggregates used in this investigation. Two LVDT displacement gauges were attached diametrically opposite each other on each core and strain measurements were taken over a length of 50mm.

The cores were tested in the Amsler type 103 compression testing machine which has a capacity of 2000 kN. The load and axial deformations of the specimens were autographically recorded by a Graphtech Data Recorder on an XY plotter over one cycle of loading and unloading. The cores were loaded to a maximum stress equal to approximately 25 per cent of the average unconfined compression strength values respectively determined by Davis and Alexander (1992) as 250 MPa, 190 MPa and 527 MPa for the quartzite, granite and andesite from the same sources.

Concrete Mixture proportions

A total of six mixtures were prepared, using water/cement (w/c) ratios of 0.56 and 0.4, for each of the three aggregate types included in the investigation. For each mix, a constant water content of 195 l/m³ was used. The w/c ratios of 0.56 and 0.4 were chosen to respectively represent typical medium and high strength concretes used in practice. This approach ensured that, for the different aggregate types used, concretes with the same w/c ratio had the same volume of cement paste. Table 1 shows the mix proportions of the six concretes as well as the slump values obtained for the concretes.

Table 1: *Mix Proportions and slump test results of the concrete used in this investigation*

Aggregate Type	Quartzite		Granite		Andesite	
Mix Number	Q1	Q2	G1	G2	A1	A2
Water (l/m³)	195	195	195	195	195	195
Cement (kg/m³)	348	488	348	488	348	488
19mm Stone (kg/m³)	1015	1015	965	965	1135	1135
Crusher Sand (kg/m³)	810	695	880	765	860	732
w/c Ratio	0.56	0.4	0.56	0.4	0.56	0.4
a/c Ratio	5.24	3.50	5.30	3.55	5.73	3.83
Slump (mm)	90	50	115	70	95	55
Compressive Strength (MPa)	37	65	38	65	48	74

Preparation of concrete specimens

Six 100mm cubes were cast for each of the six mixes. In the case of each mix, three cubes were tested at seven days and three at 28 days after casting. The 28 day strength of each concrete, which is shown in Table 1, was taken as the average of the three compressive strength tests at that age. For each concrete type, six prisms, measuring 101.6 x 101.6 x 200mm, were prepared for the creep and shrinkage testing. All the concrete samples were cured in a water bath, at a temperature maintained at 22 ± 1°C.

At approximately 21 days after casting, the prisms were removed from the curing bath and Demec targets were glued onto two opposite, formed sides of each prism, on a vertical axis symmetrically about the middle of the specimen, to accommodate a 100mm Demec strain gauge. A quick-setting glue (Schnellklebstoff X 60 Epoxy Glue) which adheres to wet concrete was used for this purpose. After the glue had set (approximately 15 minutes after application) the prisms were returned to the curing bath where they remained for a total of 28 days after casting.

Creep and associated shrinkage tests

The prisms were removed from the curing bath at age of 28 days after casting and, for each mix, three prisms were used for determining the total deformation under load. The other three prisms were used for monitoring the drying shrinkage strains in the same environment as the creep samples but in an unloaded condition. Initial elastic strains were determined by obtaining strain measurements on each of the loaded samples within 10 minutes of the application of the full load on the samples.

The loading frames were developed by Ballim (1983) and are based on the ASTM C512-76 (1976) creep frame, except the load is applied by a hydraulic flat jack instead of a compressed spring. The loaded prisms in the creep frames are shown in Figure 1 and the companion drying shrinkage samples in Figure 2.

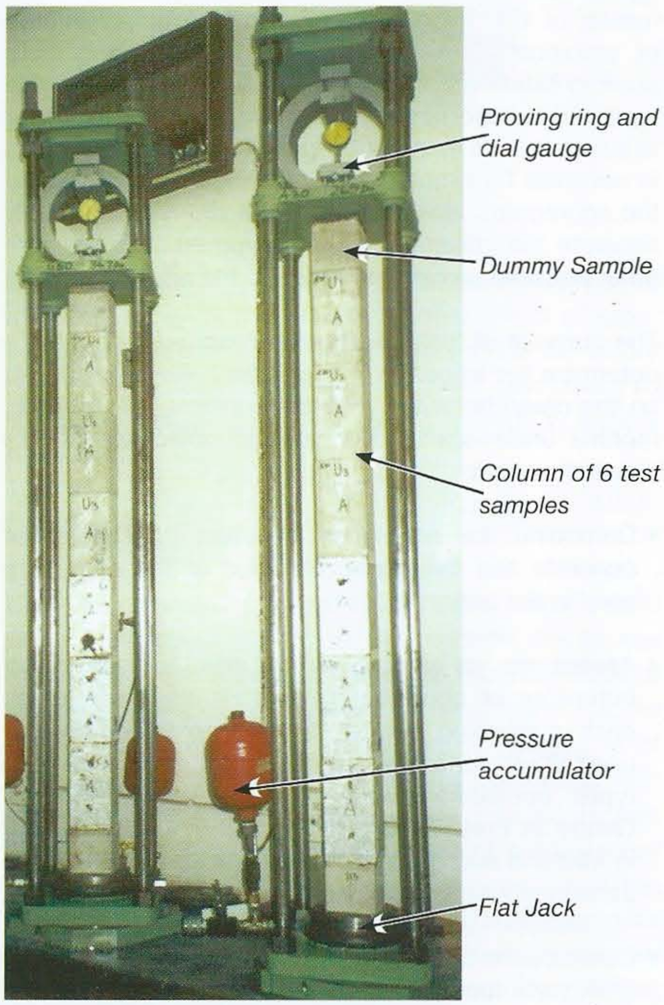

Figure 1: Loaded prisms in creep frames

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Figure 2: Companion drying shrinkage samples

By means of an air conditioner and humidifier, the temperature and relative humidity in the room in which the frames were housed was kept between 23 ± 3°C and 65 ± 5°C, respectively. The prisms in each of the six creep frames were subjected to a constant stress equal to 25 per cent of the 28 day compressive strength of the relevant mix. The stresses were maintained to an accuracy of ± 0,5 MPa for a period of six months.

In both the creep and shrinkage tests, strains were measured using a 100mm Demec gauge across steel targets which had been glued onto opposite faces of the test prism. The Demec gauge is accurate to approximately 17 microstrain. Total strains were determined daily for one week, weekly until the end of one month, and approximately monthly thereafter for a total period of six months.

At each measuring period, the strain of each prism was taken as the average of the strains measured on the two opposite faces of the prism. The strain of each group of three prisms was taken as the average of the strains of the prisms in that group.

Results and Discussion

Determination of Creep Strain

The creep strain at any time was determined as:

$$\varepsilon_c(t) = \varepsilon(t) - \varepsilon_e - \varepsilon_{sh}(t) \quad (1)$$

where,

$\varepsilon_c(t)$ = creep strain at any time t

$\varepsilon(t)$ = measured strain on the loaded samples at any time t

ε_e = average instantaneous elastic strain recorded immediately after loading

$\varepsilon_{sh}(t)$ = drying shrinkage strain at any time t (from companion samples)

In order to provide a basis for comparing the creep strains of concretes with different strengths and different applied loads, the results are presented in the form of specific creep (Cc), which is defined as:

$$C_c = \varepsilon_c(t)/\sigma \quad (2)$$

C_c therefore represents the creep strain per unit of applied stress. Details of the magnitudes of the elastic strains at loading and creep and shrinkage strains with time are given in the work of Fanourakis (1998).

Drying shrinkage strains

As the shrinkage strains were used in the analysis of the creep strains, it is appropriate to comment on the measured shrinkage of the companion samples. The average cumulative drying shrinkage strain with time measured on the companion specimens of mixes with a w/c ratio of 0.56 (Q1, G1, A1) and those measured on the specimens with a w/c ratio of 0.4 (Q2, G2, A2) are shown in Figures 3 and 4, which are plotted to the same scale.

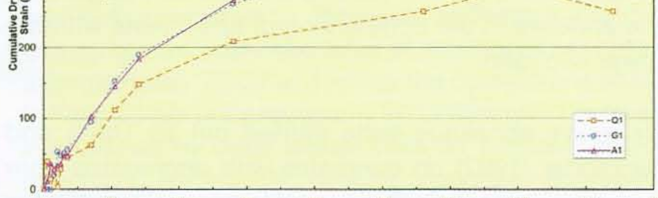

Figure 3: Cumulative drying shrinkage strain versus time of drying for shrinkage specimens with a w/c ratio of 0.56

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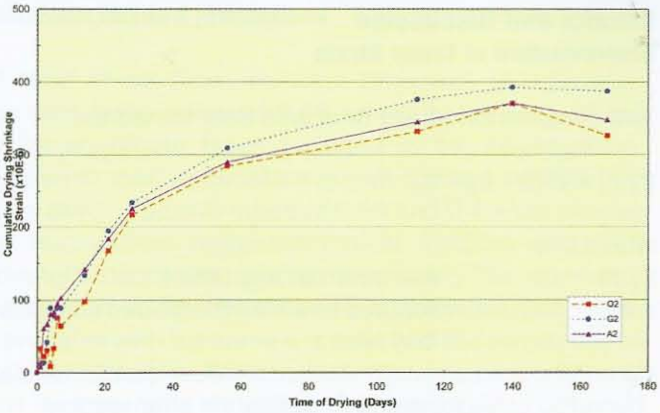

Figure 4: Cumulative drying shrinkage strain versus time of drying for shrinkage specimens with a w/c ratio of 0.4

With reference to Figures 3 and 4, it is evident that, for each aggregate type, the specimens with the higher w/c ratio (0.56) exhibited less drying shrinkage than those with the lower w/c ratio (0.4). In addition, it was noted that the difference between the shrinkage of the two strength grades of each aggregate type appears to reduce with time and the rate of shrinkage of all the mixes decreases with time. These trends are in agreement with the findings of Alexander (1993b).

The decrease in cumulative shrinkage at an age of 168 days (after loading), which is most pronounced for the quartzite concretes, is probably attributable to the increase in both relative humidity and temperature which resulted from a temporary breakdown of the air conditioner during the week in which those shrinkage strains were recorded.

Furthermore, the concretes containing quartzite aggregate displayed less shrinkage than both the granite and andesite concretes, for both w/c ratios. The specimens containing granite generally exhibited less shrinkage than those containing andesite in the case of the high w/c ratio, but more shrinkage than the andesite in the comparison of specimens with the lower w/c ratio.

Extensive shrinkage tests carried out by Davis and Alexander (1992) on concretes with aggregates from the same sources as those used in this project showed the relative shrinkage of the concrete containing granite to be higher than that of concrete containing quartzite but lower than andesite concrete.

This order of relative shrinkage with the use of different aggregates is generally but not precisely reflected in Figures 3 and 4. Nevertheless, according to Davis and Alexander (1992), the relative shrinkage values are intended for general guidance as the shrinkage of concretes containing aggregates from a particular source can vary significantly.

Correlation of total creep with E of aggregate

The measured elastic moduli, ranges and averages for each of the three aggregate types (determined in this research) are shown in Table 2. The results for the granite represent the range and the average for the six cores tested, as the visually different boulders did not show different results. This table also includes the range and average values determined by Davis and Alexander (1992) for the same aggregates from the same sources.

For the purposes of comparing the influence of aggregate alone on specific total creep, the specific total creep values at 168 days (six months) after loading were modified to account for the different w/c ratios. This modification, which is similar to one carried out by Davis and Alexander (1992), entails adjusting the specific total creep values by the ratio of their compressive strengths at the age of loading, to the mean of the compressive strengths of all six mixes (54.5 MPa). The average of the two adjusted specific creep values for each aggregate type was then expressed as a ratio of the mean of the six adjusted values (61.549 x 10-6/MPa), to obtain a relative creep value for each aggregate type. The adjustment factors, adjusted specific total creep values and relative creep factors are given in Table 3 which includes the relative creep values determined by Davis and Alexander (1992) for the same aggregates.

Table 2: *Results of elastic moduli tests on cores*

	Elastic Moduli of Rock Cores			
	Measured		Davis and Alexander	
Aggregate Type	Range (GPa)	Mean (GPa)	Range (GPa)	Mean (GPa)
Quartzite (Ferro)	59 - 88	73	42 - 98	70
Granite (Jukskei)	66 - 80	70	27 - 93	60
Andesite (Eikenhof)	82 - 94	89	80 - 110	95

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Table 3: *Adjusted specific creep values, elastic moduli and relative creep coefficients*

Measured							Davis and Alexander	
		Specific Total Creep at 168 days						
Mix	Adjustment Factor	Actual ($x10^{-6}$/MPa)	Adjusted ($x10^{-6}$/MPa)	Mean for Aggregate ($x10^{-6}$/MPa)	E (GPa)	Relative Creep	E (GPa)	Relative Creep
Q1	0.679	86.359	58.638					
Q2	1.193	45.733	54.559	56.599	73	0.92	70	0.96
G1	0.697	80.653	56.215					
G2	1.193	51.902	61.919	59.067	70	0.96	60	0.74
A1	0.880	76.997	67.757					
A2	1.358	51.699	70.207	68.982	89	1.12	95	1.19

Figure 5 shows a correlation of the relative creep with average elastic modulus of the aggregate using the specific total creep results from this investigation and from the work by Davis and Alexander (1992). The letters Q,G and A denote quartzite, granite and andesite concretes, respectively. The results in Figure 5 indicate significant variations in the stiffness of aggregates from a particular source. Furthermore, the results show that, counter-intuitively, the higher the average elastic modulus of an aggregate, the higher is the relative creep of the concrete. The regression equations and correlation coefficients applicable to the results from this investigation and from Davis and Alexander's (1992) work, when considered separately and together, are given in Table 4.

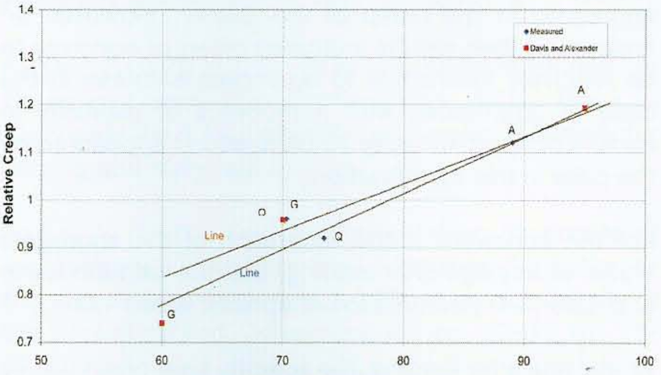

Figure 5: Relationship between relative creep and elastic modulus of aggregates

Table 4: *Correlation of relative creep to average modulus of elasticity of aggregates for the data shown in Figure 5*

Line	Data Source	Regression Equation	Correlation Coefficient (r)
A	Measured	y = 0.010x + 0.229	0.941
B	Davis and Alexander	y = 0.012x + 0.052	0.973
	Combined	y = 0.012x + 0.092	0.965

The correlations in Figure 5 show an opposite trend to those established by Rusch et al., (1962) and The Concrete Society (1974) which indicate that the higher the elastic modulus of the aggregate, the greater the restraint offered by the aggregate to the creep of the paste. However, their work included a wide spectrum of materials as aggregates, ranging from lightweight materials to normal density rock aggregates. An analysis of their results shows that creep of concrete becomes relatively insensitive to aggregate stiffness in the case of aggregates with a modulus of elasticity in excess of approximately 70 GPa. Hence, the correlations shown in Figure 5 are not necessarily in conflict with the trends established by other researchers for the fairly narrow spectrum of normal density concrete aggregates assessed in this investigation. In a separate analysis, Alexander (1993a) also found no correlation between the magnitude of the creep of concrete and the elastic modulus of the aggregate used in the concrete.

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From the above, it is clear that, for the range of aggregates assessed, the effect of variations in the elastic modulus of the aggregate on creep deformation is overshadowed by other factors which appear to be related to the geological origin of the aggregate but remain un-quantified at this stage.

Time dependent creep strain

The specific total creep (basic and drying creep) values measured on the prisms of each of the six mixes since the time of first loading are shown in Figure 6.

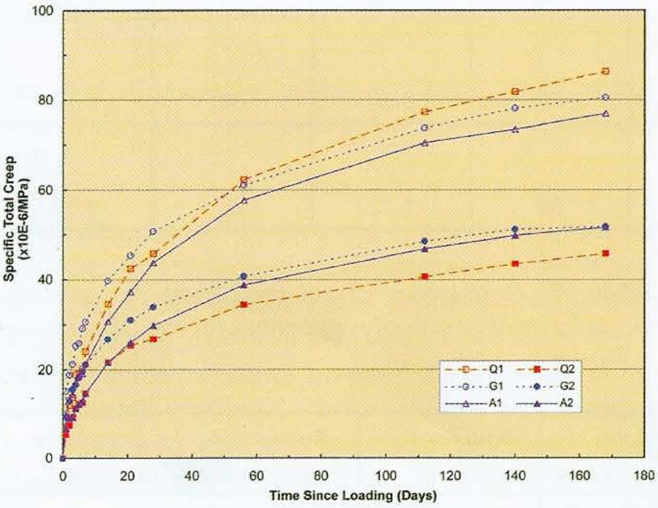

Figure 6: Specific total creep versus time since loading

It is evident from Figure 6 that, for each of the aggregate types, the mix with the lower w/c ratio (stiffer mix) yielded a lower specific total creep value. This is in accordance with the findings of Reutz (1965), Ballim (1983), Smadi et al., (1987), Addis (1992) and Fiorato (1995).

The reason for the abovementioned trend is that the concrete with the higher strength and stiffness has a relatively lower porosity of the hardened cement paste matrix in comparison with the lower strength concrete (Muller and Kuttner, 1996). Furthermore, the curves of the higher w/c ratio (0.56) mixes indicate that the order of increasing specific total creep of concrete, for most of the test period, with the use of the different aggregates, to be andesite, granite and quartzite. By relative comparison, the positions of the specific total creep curves of the lower w/c ratio (0.4) mixes differ in that the quartzite concretes yielded the lowest specific total creep values. Hence, when considering the average elastic modulus values of the three aggregate types, which are given in Table 3, it is evident that no correlation exists between the specific total creep of the concrete and the stiffness of the aggregate included in the concrete.

The investigation conducted by Davis and Alexander (1992) on creep of concretes with various aggregates, including those used in this research, showed concrete creep with the use of these aggregates to increase in the order granite, quartzite and andesite. Referring to Figure 6, it is evident that the positions of the specific total creep curve of the andesite concretes (in the case of the higher w/c ratio) and the granite concretes (in the lower w/c ratio) are in disagreement with the results of Davis and Alexander (1992). This further reinforces the point that, in this narrow range of aggregate elastic moduli, variations in concrete creep deformation characteristics cannot be explained by variations in the elastic modulus. The reasons for these variations need to be sought in other parameters related to the geological origin of the aggregate and its interaction with the cement paste.

Conclusions

The specific total creep values at six months after loading were modified to relative creep values to eliminate the expected influence of the different w/c ratios on the creep exhibited. These results indicated that a significant positive correlation exists between the relative creep of concrete and the elastic modulus of the included aggregate. For the concretes of each aggregate type, the higher the elastic modulus of the aggregate, the more the relative creep of the concrete. An identical trend was established using data from Davis and Alexander (1992) for the same aggregates as those considered in this investigation but pertaining to an age of five years after loading. These correlations show an opposite trend to those established by Rusch et al., (1962) and The Concrete Society (1974), which indicate that the higher the elastic modulus of the aggregate, the greater the restraint offered by the aggregate to the creep of the paste. However, an analysis of their results indicates creep of concrete to be relatively insensitive to aggregate stiffness in the case of aggregates with a modulus of elasticity in excess of approximately 70 GPa, which appears to be the case in this investigation.

For the concretes made with each of the aggregate types, at any age after loading, the mix with the lower w/c ratio (0.4) yielded a lower specific creep value.

At any age after loading, the specific total creep values for the lower w/c ratio mixes, with the use of the different aggregates included in this research, increase in the order quartzite, andesite and granite. In the case of the higher w/c ratio, the specific total creep values of the concretes made with different aggregates increase in the order andesite, granite and quartzite. These results confirm that, for the fairly narrow spectrum of normal density aggregates with relatively high elastic moduli that were included in this investigation, no correlation exists between the creep of concrete and the stiffness of the included aggregate.

The unexpected abovementioned results appear to be attributable to the stress strain behaviour of the aggregate/paste interfacial zone, which is in turn dependant on the density of the zone and the strength of the bond between the aggregate and the paste.

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References

Addis, B.J. (1992) Properties of High-Strength Concrete made with South African Materials, PhD thesis, University of the Witwatersrand, Johannesburg.

Alexander, M.G. (1993a) Properties of Aggregates in Concrete, Report on Phase 2 testing of concretes made with aggregates from a further 10 different quarries, and associated design recommendations, Research Report, Department of Civil Engineering, University of Cape Town, Rondebosch, pp. 23, 32, 75, 76, 85.

Alexander, M.G. (1993b) Two experimental techniques for studying the effects of the interfacial zone between cement paste and rock, Cement and Concrete Research, Vol. 23, No. 3, May, pp. 567-576.

ASTM C512-76 (1976) Standard Method of Test for Creep of Concrete in Compression, ASTM Book of Standards, Part 14, Philadelphia: American Society for Testing and Materials.

Ballim, Y. (1983) The Concrete Making Properties of the Andesite Lavas from the Langeleven Formation of the Ventersdorp Supergroup, MSc thesis, University of the Witwatersrand, Johannesburg, pp. 22-31, 67, 71-73, 80.

BS 1881 (1983) Testing Concrete, Part 121: Method for Determination of Static Modulus of Elasticity in Compression, London: British Standards Institution.

Davis and Alexander (1992) Properties of Aggregates in Concrete (Part 2), Hippo Quarries Technical Publication, Sandton, South Africa, Mar., pp. 1-27, 42-43, 46-47.

Fanourakis, G.C. (1998) The Influence of Aggregate Stiffness on the Measured and Predicted Creep Behaviour of Concrete, MSc (Eng) dissertation, University of the Witwatersrand, Johannesburg.

Fiorato, A.E. (1995) Engineering properties of high-strength and conventional strength concretes, Proceedings of the Third National Concrete & Masonry Engineering Conference, San Francisco, California, June, pp. 13.

Muller, H.S. and Kuttner, C.H. (1996) Creep of high-performance concrete - characteristics and code-type prediction model, Proceedings of the Fourth International Symposium on Utilization of High-Strength/High-Performance Concrete, Paris, pp. 378, 379.

Reutz, W.A. (1965) A hypothesis for the creep of hardened cement paste and the influence of simultaneous shrinkage, The Structure of Concrete, proceedings of an international conference, London, Sept., pp. 319-344.

Rusch, H., Kordina, K. and Hilsdorf, H.K. (1962) Der einfluss des mineralogischen charakters der zuschlage auf das kriechen von beton, Deutscher Ausschuss fur Stahlbeton, Berlin, No. 146, pp. 19-133.

Smadi, M.M., Slate, F.O. and Nilson, A.H. (1987) Shrinkage and creep of high-, medium-, and low-strength concretes, including overloads, ACI Materials Journal, Mar./Apr., pp. 229.

Soroka, I. and Jaegermann, C.H. (1972) Properties and possible uses of concrete made with natural lightweight aggregate, Part 1, Report to the Ministry of Housing, Haifa Technion.

The Concrete Society (1974) The Creep of Structural Concrete, London: The Society, Technical Paper No. 101.

Troxell, G.E., Raphael, J.M. and Davis, R.E. (1958) Long-time creep and shrinkage tests of plain and reinforced concrete, Proceedings ASTM, Vol. 58, pp. 1101-1120.