Int. J. of GEOMATE, Sept., 2014, Vol. 7, No. 1 (Sl. No. 13), pp.974-979
Geotech., Const. Mat. & Env., ISSN:2186-2982(P), 2186-2990(O), Japan

STRESS - STRAIN BEHAVIOUR OF SLAG CEMENT CONCRETE

Mustapha Boukendakdji

Civil Engineering Department, Faculty of Engineering, University of Hail, Saudi Arabia

ABSTRACT: The paper describes the results of test carried out on OPC concrete and slag cement concretes. Ten blended slag-cement concretes, made with typical slags from four countries (United Kingdom, Belgium, South Africa and Japan), are compared with a control OPC concrete. The slags replaced 30 to 70% of cement by mass. The bobbin shaped specimens were used in the direct tension test and 300x150 mm dia. cylindrical specimens were used in the axial and lateral strain tests. Poisson's ratio in compression was determined as the ratio of the lateral to axial strain at the ages of 14 and 84 days. Concretes at the age 84 days exhibits more linearity than at the age of 14 days and slag concrete becomes more brittle when stored in the dry environment. There was no difference between the Poisson's ratio of slag and OPC concretes.

Keywords: Slags, Stress-strain, Compression, Tension, Poisson's ratio

1. INTRODUCTION

The main objective of this investigation was to study the stress-strain of concrete containing different slags as a cement replacement in compression and tension.

From typical stress-strain curves for aggregates, hydrated cement paste, and concrete loaded in uniaxial compression, relative to aggregate and cement paste, concrete is really not a linear elastic material. The deformation of concrete under a short-term loading has been shown to be directly related to progressive internal microcracking at both the cement paste-aggregate interface and through the mortar itself [1], [2]. The non-linearity of the stress-strain relation is related to the cumulative effects of this cracking. Such microcracking occurs as a result of differential volume changes between the cement paste and the aggregate, i.e. due to differences in stress-strain behaviour, and in thermal and moisture movements.

The rate of strength development at early ages is generally inversely proportional to the amount of slag used in the blend because the initial rate of reaction of slag and water is slower than that of OPC and water [3]. Brooks and Neville [4] found that the secant modulus in tension is greater than that in compression and Stutterheim [5] found that for water-stored specimens poisson's ratio was substantially the same irrespective of the cement type and ranged between 0.23 and 0.3.

EXPERIMENTAL DETAILS

The materials used to make eleven concretes were ordinary Portland cement (OPC), ground granulated blastfurnace slag and quartzitic aggregate. Slags were obtained from the U.K., Belgium, Japan and South Africa. Chemical analysis and physical properties are given in Table1.

Table 1 Chemical analysis of OPC and slags ('%)

	OPC	U.K. slag	B. slag	S.A. slag	J. slag
SiO_2	20.5	36.11	33.08	38.59	32.99
Al_2O_3	5.79	10.84	12.93	12.94	15.20
Fe_2O_3	2.50	0.38	1.17	0.56	0.37
CaO	65.8	40.45	39.80	35.02	42.49
MgO	1.25	9.46	9.79	9.40	6.22
MnO	0.08	0.57	0.50	1.07	0.49
TiO_2	0.25	0.70	0.57	0.64	0.98
Sulphur	0.97	1.22	1.13	0.89	0.83
Sulphide	0.04	1.13	1.07	0.82	0.78
SO_3	2.33	0.28	0.15	0.18	0.13
Na_2O	0.28	0.32	0.40	0.22	0.24
K_2O	0.62	0.51	0.60	0.78	0.36
L.O.I	1.27	1.78	0.98	0.05	0.53
Fineness (m^2/kg)	391	412	402	407	465
Potential compound composition					
C_3S	62.73				
C_2S	11.59				
C_3A	11.12				
C_4AF	7.6				
chemical modulus		1.68	1.89	1.48	1.96

$$\text{chemical modulus} = \frac{CaO + MgO + Al_2O_3}{SiO_2}$$

The first concrete was an OPC control mix having mass proportions of 1:1.62:2.49 with a water/cement ratio of 0.43 and the cement content was 437 kg/m^3 . The ten slag concretes had 30 to 70% of the mass of OPC replaced by equal masses of slags, with the same aggregated proportions and water/cementitious ratio as the control concrete.

All moulded specimens were cured for 24 hours under wet hessian, then demoulded and cured in water for 13 days. Thereafter, the specimens were stored in two storage environments: in water at 20± 2^o C;, and in air at 65±5% RH and 20±2^o C.

The bobbin shaped specimens were used in the direct tension test and 300 x 150 mm dia. cylindrical specimens were used in the axial and lateral strain tests. The strain gauges used were 60 mm and 30 mm foil electrical resistance and were embedded in both the bobbin and the cylindrical specimens; the 30 mm gauges were used for lateral strain, and the 60 mm gauges for axial strain. The ages of testing were 14 and 84 days and the average curve of two specimens was obtained.

Secant modulus of elasticity in compression and tension were obtained at a stress equal to 0.3 of the strength. Poisson's ratio in compression was determined as the ratio of the lateral to axial strain at the ages of 14 and 84 days. In addition, for each mixture, 100 mm cubes were made to determine the compressive strength

TEST RESULTS AND DISCUSSION

Compressive Strength

Figure 1 shows the average influence of replacement of cement by slag on strength of water-stored concrete.

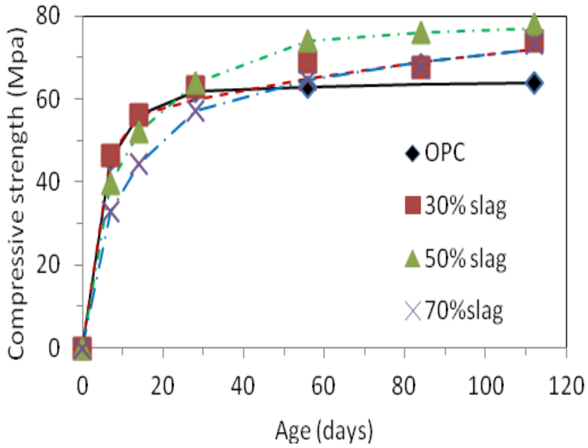

Fig. 1 Average influence of cement replacement by slag on compressive strength.

The behaviour follows the expected trend in that an increase of slag content reduces the early-age strength, but later-age strengths are similar to, or slightly greater than, the strength of OPC concrete. For concrete stored dry from the age of 14 days, the strength was greater than for wet storage. The 300 x 150 mm dia. cylinder strength followed the same pattern, and the relationship between the two strengths was similar for both the wet and dry storage conditions. The mean and standard deviations of the cylinder to cube strength ratio was 0.82 ± 0.042, which is close to the generally accepted ratio of 0.80.

Stress-Strain in Compression

Figures 2 to 4 show the stress-strength ratio plotted against axial and lateral strain as measured on 150 x 300 mm. cylindrical specimens for OPC, 50% U.K.slag and 50% S.A.slag cement concrete, respectively. It can be seen that the shape of the curves are similar for OPC and slag concretes. The maximum variability was ± 6 and ± 25% for the stress-strain test in axial and lateral, respectively.

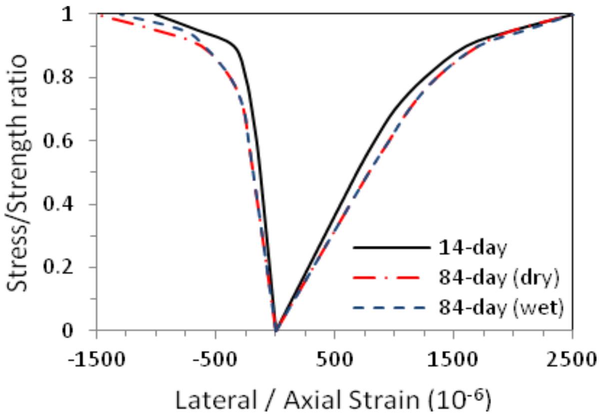

Fig. 2 Stress-strain curves for OPC concrete in compression.

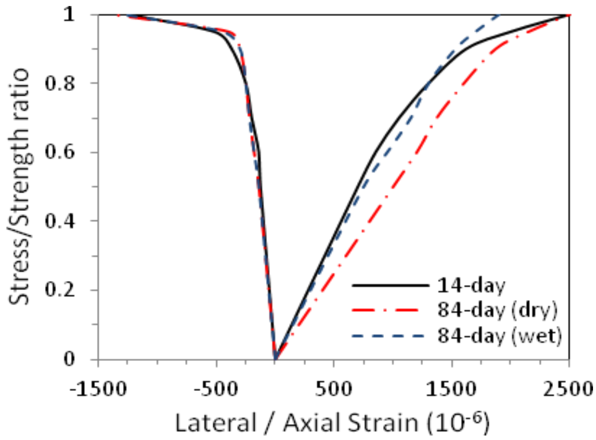

Fig. 3 Stress-strain curves for 50% U.K.slag concrete in compression.

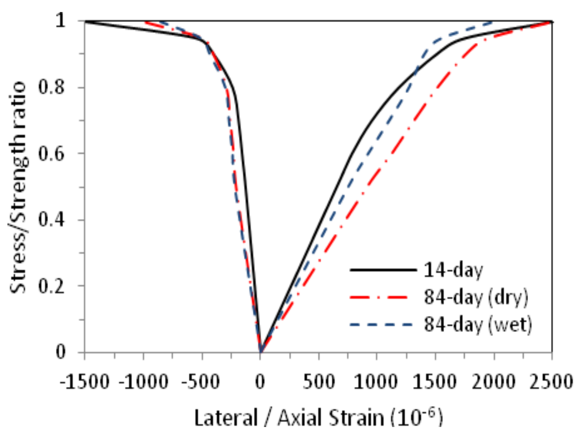

Fig. 4 Stress-strain curves for 50% S.A.slag concrete in compression.

The secant modulus of elasticity, as measured at a stress-strength ratio of 0.3 is shown in Table 2. Compared with OPC concrete, the 14-day values of slag-cement concrete are similar, but the 84-day strengths are greater. The 84-day modulus of dry-stored slag-cement concrete was less than for wet-storage by approximately 12%. However, for OPC dry-stored concrete, the 84-day modulus was 14% greater than for wet storage.

Table 2: Secant modulus of elasticity of water-cured OPC and slag concretes obtained from 150 x 300 mm cylinders (GPa)

Age (days)		14	84	84 *
Control Mix		31.5	33.9	38.6
U.K.slag	30%	27.8	37.1	33.8
	50%	29.9	37.3	31.9
	70%	27.4	38.6	33.2
B.slag	30%	30.4	35.1	30.9
	50%	28.4	39.5	34.5
	70%	27.6	35.5	32.3
S.A.slag	50%	30.6	41.6	36.8
	70%	32.1	38.4	34.5
J.slag	50%	28.1	41.6	32.6
	70%	26.1	35.9	33.7

* specimens were stored in dry environment after 14-days of water curing and tested dry.

A comparison of the strain at which the initial secant modulus decreased by 5% is made. A similar approach has been adopted previously by Kaplan [6]. The strain measured at this particular point is defined as the strain at the limit of proportionality (L.O.P.) and the values obtained are tabulated in Table 3. It appears that generally, the strain increases with age which implies concrete at the age 84 days exhibits more linearity than at the age of 14 days. This difference is probably due to the fact that the concrete tested at 84 days is stronger; Mindess and Young [7] have stated that stronger concrete exhibits a more linear stress-strain behaviour because it leads to a higher bond-strength between aggregate and cement paste, and the curve also becomes more linear when the stiffness of the matrix approaches the aggregate stiffness and it is known that stiffness of the matrix increases with age.

Table 3 Axial strain in compression at limit of proportionality (L.O.P.) of OPC and slag concretes (Microstrain).

Age (days)		14	84	84 *
Control Mix		440	550	555
U.K.slag	30%	785	625	952
	50%	672	555	1375
	70%	745	932	1350
B.slag	30%	490	602	905
	50%	640	930	860
	70%	420	560	750
S.A.slag	50%	600	945	917
	70%	350	864	1400
J.slag	50%	410	575	950
	70%	420	920	1010

* specimens were stored in dry environment after 14-days of water curing and tested dry.

It seems that while the effect of storing slag concrete specimens in the dry environment is to increase the strain at L.O.P., compared with those stored wet, there was no effect on OPC concrete. Therefore, it can be concluded that the slag concrete becomes more brittle when stored in the dry environment. It is difficult to notice any differences between the effect of slag types or slag content in view of the scatter.

As the stress-strength ratio versus axial strain curve becomes asymptotic at failure, it is difficult to assess any value for limiting axial strain. However, comparison can be made on the basis of 95% of failure stress, i.e. the stress at a stress-strength ratio of 0.95. These values are tabulated in Table 4.

Table 4 Axial strain at a stress:strength ratio of 0.95 of OPC and slag concretes (Microstrain).

Age (days)		14	84	84 *
Control Mix		1750	1930	1850
U.K.slag	30%	1950	1510	1780
	50%	1900	1680	2065
	70%	1745	1642	1915
B.slag	30%	1875	1650	2110
	50%	1725	1600	1860
	70%	1585	1595	1865
S.A.slag	50%	1735	1535	1920
	70%	1585	1735	1852
J.slag	50%	1820	1784	2426
	70%	1640	1860	2313

It can be seen that for concrete stored wet and tested at 84 days, the slag concrete has a lower limiting axial strain than OPC concrete. On the other hand, for concrete stored dry, the limiting axial strain was similar or higher in the case of slag concrete. Also, for any slag concrete mix, the effect of storing concrete dry after 14 days of water-curing was to increase the limiting axial strain which implies that dry specimens can withstand higher axial strain at failure compared with those wet stored in the case of slag concrete.

A comparison of the limiting lateral strain at a stress-strength ratio of 0.95 is given in Table 5 and there are no apparent differences between OPC and slag concretes at the age of 14 days, the average value being about 560 microstrain. On the other hand, generally at 84 days, the OPC concrete exhibited higher limiting lateral strain for both wet and dry storage conditions which implies more ductile behaviour and the capacity to sustain a higher stress. This may explain the higher indirect tensile strength of slag concrete compared to OPC concrete [8].

Table 5: Lateral strain at a stress:strength ratio of 0.95 of OPC and slag concretes (Microstrain).

Age (days)		14	84	84 *
Control Mix		550	775	887
U.K.slag	30%	540	372	702
	50%	500	445	405
	70%	595	300	510
B.slag	30%	462	500	610
	50%	445	560	475
	70%	610	460	475
S.A.slag	50%	505	497	465
	70%	525	640	415
J.slag	50%	775	700	750
	70%	650	670	700

* specimens were stored in dry environment after 14-days of water curing and tested dry.

Stress-Strain in Tension:

Figures 5 to 7 show the average stress-strain curves for OPC, 50%UK slag and SA slag concretes in tension and the maximum variability between two specimens obtained was ± 14%. It can be seen that in tension most failures were sudden. This behaviour could have been due to the fact that failure did not occur at the centre of the specimens (within the gauge length) and, therefore, strength and strain at failure may not considered to be representative. For the case of elastic-pseudo plastic behaviour (Fig. 7), the tensile strain at failure, for concrete tested at 84 days, was up to about 125 microstrain.

The development of direct tensile strength of OPC and slag-cement concretes is similar to that of compressive strength. The results of direct tensile strength of concrete are listed in Table 6. Unlike the compressive strength which was about 8% stronger for dry storage than for wet storage, tensile strength was stronger for wet storage.

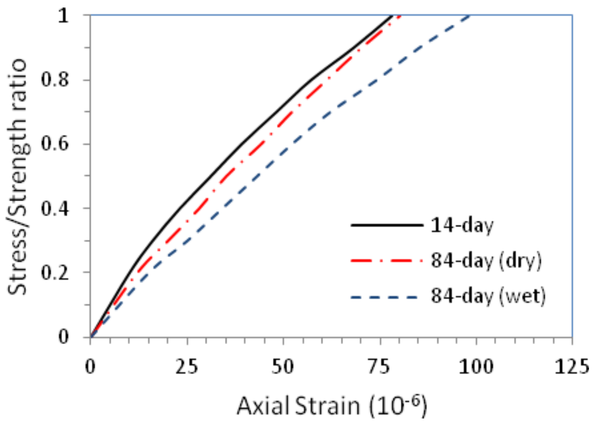

Fig. 5 Stress-strain curves for OPC concrete in tension.

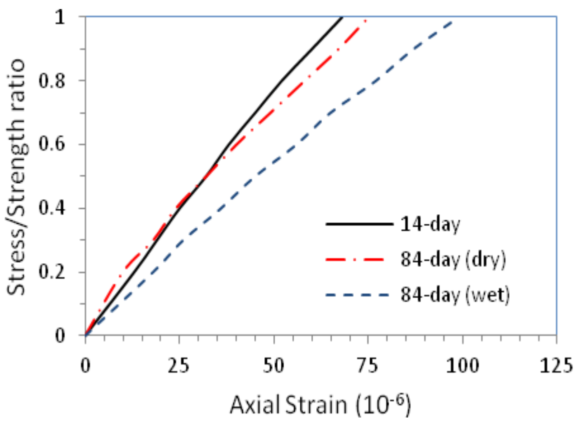

Fig. 6 Stress-strain curves for 50% U.K.slag concrete in tension.

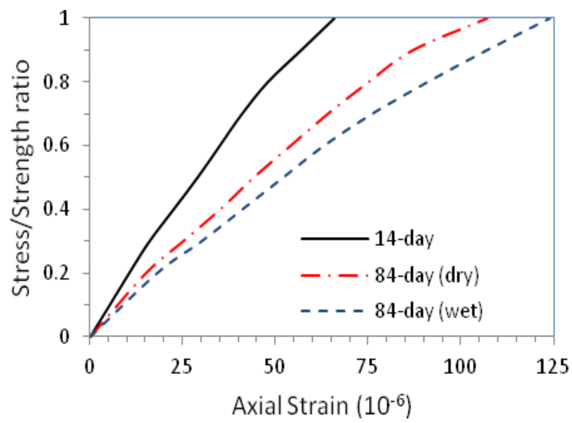

Fig. 7 Stress-strain curves for 50% S.A.slag concrete in tension.

Table 6 Direct tensile strength of OPC and slag-cement concrete (MPa).

Age (days)	storage enviro nment	OPC mix	50% U.K.slag concrete	50% S.A.slag concrete
14	water	2.30	2.35	1.54
84	air	3.13	3.13	3.52
84	water	3.74	3.72	3.74

The secant modulus calculated from these curves are tabulated in Table 7. It can be seen that the modulus increases with age following a similar trend to that of modulus in compression. The secant modulus in tension is greater than that in compression because the modulus decreases with an increase in stress [9] and the modulus in tension is measured at a lower stress than that in compression. This confirms the finding of Brooks and Neville [4] whose explanation for this trend was that, at low stresses, the stress-strain curve is concave to the stress axis owing to the closing of microcracks and, at high stresses, the stress curve is convex owing to the opening of microcracks and to creep.

Table 7: Secant modulus of water-cured OPC and slag-cement concretes in tension (GPa)

Age (days)	storage environ ment	OPC Mix	50% U.K.slag concrete	50% S.A.slag concrete
14	water	41.3	37.8	34.8
84	air	44.8	44.1	35.0
84	water	46.9	52.2	42.1

Poisson's Ratio:

Poisson's ratio at a stress-strength ratio of 0.3 represents the elastic portion of the stress-strain curve, and is generally used for practical design; the values are shown in Fig. 8. For OPC and slag concretes tested at 14 days, Poisson's ratio ranged between 0.139 and 0.22 and for slag concretes stored dry, and at 84 days the range was between 0.122 and 0.209. These values for slag concrete are lower than those of the same concrete stored in water; the latter varied between 0.161 and 0.24. This difference is mainly due to the fact that the wet-stored slag concrete exhibited a higher axial strain than that stored dry, whilst the lateral strains remained fairly constant. This confirms the conclusion of Mindess and Young [7] that Poisson's ratio of saturated concretes lies in the range 0.2 to 0.3, but decreases to about 0.18 on drying. However, the Poisson's ratio of OPC concrete stored either in water or dry are similar (Fig. 8) because the axial strains of specimens stored dry or in water are similar. From the results shown in Fig. 8 it is not easy to see any effect of slag content or slag type on the Poisson's ratio due to the scatter of the results. Also, there does not seem to be difference between Poisson's ratio of slag concrete and OPC concrete, apart from the effect of storage environment. Stutterheim [5] found that for water-stored specimens Poisson's ratio was substantially the same irrespective of the cement type and ranged between 0.23 to 0.30 at the age of 28 days.

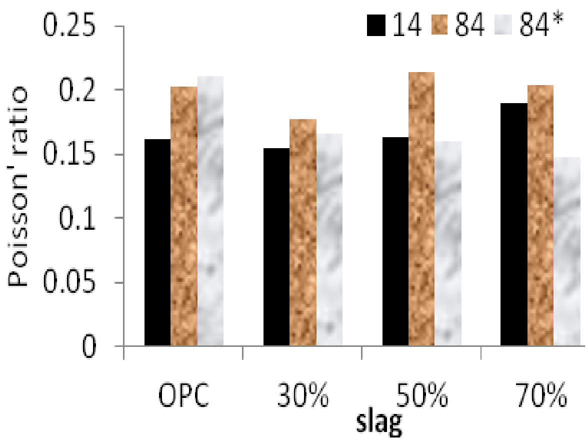

Fig. 8 Poisson's ratio at a stress:strength ratio of 0.3 of water-cured OPC and slag concretes.

CONCLUSION

For the range of typical international slags and replacement levels used in this investigation, a comparison with OPC concrete had led to the following conclusions:

1) An increase of slag content reduces the early-age strength, but later-age strengths are similar to, or slightly greater than, the strength of OPC concrete which confirms the conclusion of Boukendakdji [10].

2) The secant modulus of elasticity in compression of water-stored slag-cement concretes was similar at early ages, and greater at later ages. However, the opposite trend occurred for mature dry-stored concrete.

3) Concretes at the age 84 days exhibits more linearity than at the age of 14 days and slag concrete becomes more brittle when stored in the dry environment.

4) The secant modulus in tension is greater than that in compression

5) There was no difference between the Poisson's ratio of slag and OPC concretes which confirms the conclusion of Stutterheim [5]. However, the values for specimens stored dry was slightly higher than those stored wet for slag concretes.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the facilities and assistance provided by the University of Hail. The support of this research program by The Saudi Binladin Group is gratefully acknowledged as well.

REFERENCES

[1] Hsu, T.C. et al. "Microcracking of plain concrete and the shape of the stress-strain curve", American Concrete Institute Journal, Vol.60 No.2, 1963, pp.209-223.

[2] Shah, S.P. and Winter, G. "Inelastic behaviour and fracture of concrete", American Concrete Institute Journal, Vol.63, No.9, 1966, pp.925-930.

[3] Boukendakdji, M. "Mechanical properties and long-term deformation of slag cement concrete", PhD thesis, Dept. of Civil Engineering, University of Leeds, 1989, 290 pp.

[4] Brooks, J.J. and Neville, A.M. "A comparison of creep, elasticity and strength of concrete in tension and in compression" Magazine of Concrete Research, Vol.29, No.100, 1977, pp.131-41.

[5]. Stutterheim, N. "Properties and uses of high - magnesia Portland slag cement concretes" American Concrete Institute Journal, Vol.56, April, 1960, pp.1027-45.

[6] Kaplan, M.F. "Strains at stresses of concrete at initiation of cracking and near failure" ACI journal, July 1963, pp.853-78.

[7] Mindess, S. and Young, J.F. Concrete, New Jersey, Prentice-hall, Inc, Englewood Cliffs, 1981.

[8] Boukendakdji, M , Brooks, J.J. and Waiwright, P.J. "Strength Development of Concrete with and without slag" ConChem International Exhibition and Conference, Brussels, Belgium, 28-30 Nov. 1995.

[9] Neville, A.M. Properties of concrete, London, Pitman third edition, 1981.

[10] Boukendakdji O., Kadri E., and Kenai S. “Effects of granulated blast furnace slag and superplasticizer type on the fresh properties and compressive strength of self-compacting concrete” Cement and concrete composites, Vol 34, 2012, pp 583-590.

Int. J. of GEOMATE, Sept., 2014, Vol. 7, No. 1 (Sl. No. 13), pp.974-979.

MS No. 3252 received on June 15, 2013 and reviewed under GEOMATE publication policies.

Corresponding Author: Mustapha Boukendakdji