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Engineering Properties of Concretes with Combinations of Cementitious Materials

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Synopsis: The overall objective of this paper is to establish the engineering properties of concrete containing combinations of fly ash/silica fume and slag/silica fume. Six concrete mixtures were tested, with total cementitious materials content of 350 kg/m^3 and 450 kg/m^3, and a constant water/cementitious materials ratio of 0.45. The effect of three curing conditions was investigated, and the tests were performed up to about 260 days. The results reflect conclusively that cement replacement materials reduce slightly the engineering properties of portland cement concrete, and that the exposure conditions have a strong influence on flexural strength, dynamic modulus, and ultrasonic pulse velocity. Slag was generally found to be slightly superior to fly ash in the development of these engineering properties. The key to developing fly ash/silica fume and slag/silica fume concretes without suffering a reduction of strength gain when exposed to drying environmental conditions is to incorporate within the mixtures adequate amounts of portland cement and water to ensure the continuation of pozzolanic reactivity and hydration.

Keywords: fly ash; slag; silica fume; pozzolans; compressive strength; flexural strength; dynamic modulus.

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INTRODUCTION

No construction material is inherently durable for life, or totally resistant to attack by external agents. Nevertheless, concrete is a highly durable material in most normal , and many moderately aggressive exposure conditions. However, as a result of environmental interactions and cracking, the microstructural and engineering properties of portland cement concrete change adversely with time, and a process of deterioration begins to take place. The severity of the environment is a major factor influencing and controlling the progress and process of concrete deterioration, and where climatic conditions are extreme, and the surroundings are highly contaminated with chloride, sulphate and carbonate salts, widespread and premature deterioration and degradation of concrete structures can become a common occurrence, particularly if these factors are further compounded with poor quality concrete, and/or deficiencies in design and construction practices.

Extensive laboratory tests and field performance now confirm that the most direct, technically sound and economically attractive solution to overcome the problem of lack of durability of concrete is to incorporate pozzolanic and/or cementitious by-products or mineral admixtures in portland cement concrete, in combination with an appropriate and compatible high range water reducing admixture, which can enhance the properties of the resulting concrete in both the fresh and hardened states, and particularly, its durability properties (1-3). Much of the published data, however, relate to the use of fly ash (FA), or ground granulated blastfurnace slag (Slag) or silica fume (SF) alone as partial replacement of, or an addition to, portland cement. The major drawback of using FA or slag as cement replacement material is the low and slow development of early strength, whereas high silica fume contents can lead to problems of dispersion, and even to some loss of durability (4, 5). Further, there is also some growing evidence that portland cement concrete incorporating FA, Slag or SF alone cannot give the range of properties required for long-term durable concrete performance in extreme environments such as those in the Arabian Gulf region.

The focus of the study, part of which is reported in this paper, is to develop concretes capable of attaining high early strength and withstanding attack by very aggressive agents and to reduce the risk of deterioration of concrete in extreme environments. The approach adopted in this study to achieve this is to use a minimum portland cement content with combinations of FA/SF and Slag/SF, and to examine the role and effectiveness of such combinations in improving the engineering properties, pore structure and oxygen permeability (6) of the resulting concrete through enhanced mix proportioning and proper curing. This paper presents data on the engineering properties of concretes containing mixtures of FA/SF or Slag/SF exposed to three curing conditions.

EXPERIMENTAL PROGRAM

The targeted cube compressive strength of the concretes was a minimum of 40 MPa at 7 days, and a minimum of 50 MPa at 28 days. To develop high early strength prior to 7 days, a minimum portland cement content of 250 kg/m^3 was specified. To ensure early chemical activity, and to enhance pore refinement, a controlled small amount of a highly reactive pozzolan such as SF was incorporated into all the concrete mixtures. FA and Slag were then incorporated to ensure continued long-term pozzolanic and cementitious reactivity and to enhance durability, in combinations of FA/SF and Slag/SF so that the total binder content did not exceed either 350 kg/m^3 or 450 kg/m^3.

Again, to ensure continued pozzolanic/cement reactivity, very low water-cementitious materials ratios (w/cm) were deliberately avoided. The final chosen w/cm was 0.45, and this was kept constant for all the mixtures. After several trials six concrete mixtures were chosen for further investigation, and these are shown in Table 1.

The supplementary cementitious materials were all used to replace cement by mass. The aggregate-cementitious materials ratios were kept constant at 5.26/1 and 4.06/1 for the 350 kg/m^3 and 450 kg/m^3 mixtures respectively. The per cent of sand in the total aggregate was also kept constant at 33% for all the mixtures. The aggregates were used in an air-dry condition, and the water added to the mixture was adjusted for their early moisture absorption.

All the mixtures were proportioned to have a slump in the range of 100-150 mm. To achieve this high slump, a sulphonated melamine formaldehyde high-range water reducing admixture without chlorides was incorporated in all the mixtures, and this varied from about 0.60 to 1.5% by mass of total cementitious materials content. In addition, to obtain a uniform and cohesive mixture, and to reduce bleeding, the mixing water was added in two stages and this ensured that there was practically no visible bleeding of the mixtures during casting (7). The slumps were measured immediately after casting, and the average measured slumps varied from 110 to 130 mm.

Concrete Materials

Normal portland cement ASTM C150 Type I (PC) was used throughout. The cement had a specific surface of 354 m^2/kg, and a total equivalent sodium oxide content of 0.82%. The FA, slag and SF satisfied the appropriate British Standard specifications. The FA was a low-calcium ash ASTM C618 Type F; the slag had a fineness of 417 m^2/kg, and the SF was used in the form of a slurry with 50% solid contents.

The fine and coarse aggregates were washed natural aggregates. The fine aggregate had a fineness modulus of 2.21; the coarse aggregate consisted of a mixture of rounded and crushed gravel with 10 mm maximum particle size, and a fineness modulus of 5.75. The aggregates contained very little chloride (less than 0.01%), and were innocuous to alkali-aggregate reactivity.

Test Details

The following engineering properties of the concretes shown in Table 1 are reported here, namely, compressive strength, flexural strength, dynamic modulus, shrinkage and swelling strain, and ultrasonic pulse velocity. Only one geometry of test specimen, 100 x 100 x 500 mm, was used. The flexural strength was first obtained, and the two broken halves were then used to determine the equivalent cube strength. The dynamic modulus of elasticity was determined by exciting the test specimen in the longitudinal mode of vibration. Drying shrinkage and swelling strain were measured on all sides of each prism using a mechanical extensometer over a 200 mm gage length. The ultrasonic pulse velocity was determined with a commercially available portable equipment using 50 kHz transducer of 50 mm diameter over a path length of 500 mm. Two prisms were used for each test. All the tests were carried out according to the appropriate B.S. tests.

Curing Conditions

Since FA, Slag and SF are all sensitive to curing, the curing regime was a major test variable in the study reported here. All the test specimens were left covered in the steel molds for the first 24 h after casting, then demolded, and left to cure in an internal environment of 20 ± 2°C as described below. Three curing regimes were used for this investigation.

1. Continuous water curing at 100% RH(wet-cured)
2. Continuous uncontrolled internal environment at 75-90% RH i.e., no water curing after demolding (air-cured).
3. Seven days water curing at 100% RH followed by exposure to air drying at 75-95% RH (7 days wet/air-cured).

TEST RESULTS AND DISCUSSION

Cube Compressive Strength

The early age strength development of all the water-cured FA/SF and Slag/SF concretes is shown in Tables 2 and 3 respectively. The test results show that all the concretes with FA/SF and Slag/SF combinations had lower one-day strength compared to that of the portland cement concrete. The reduction in strength both at one day and seven days was higher, the higher the total cementitious materials replacement, and generally, slag lagged slightly behind FA in the development of the one-day strength. Nevertheless, cube strengths of 15 to 24 MPa were obtained with moderate replacements of portland cement, compared to about 27 MPa of the portland cement concrete.

With continued hydration, the strength of the FA/SF mixture began to slightly lag behind that of the Slag/SF mixture, mixture Y attaining about 41 MPa cube strength at 7 days compared to about 49 MPa of the mixture Z. Both mixtures X and Z with moderate amounts of mineral admixtures were able to attain strengths similar to that of the control mixture W. All the concretes with FA/SF and Slag/SF combinations were able to attain the target cube strength of 40 MPa at 7 days, except the concrete mixture ZY with a substantial amount of slag content. These data generally confirm other published strength data, and show that concretes with large FA and Slag contents require much longer water curing to develop strengths similar to that of the portland cement concrete without any mineral admixtures, even in the presence of a small amount of other highly reactive pozzolans (3, 8). In general terms, all other conditions being equal, Slag concrete lags behind FA concrete in very early age, i.e. one day, strength development, with the slag concrete overtaking the FA concrete with continued hydration and age.

Not surprisingly, the 7-day cube strengths of all the air-cured concretes were very similar to the strengths of the water-cured samples. A limited period of exposure of 7 days to air drying in a 75-90% RH environment did little harm to the concretes, and there was no strength loss after 7-days' exposure.

The long-term strength development of all the concretes investigated is shown in Table 4. It is readily seen that all the concretes (with the exception of mixture ZY when air-cured) attained the targeted 50 MPa at 28 days; in fact, the 28 days strengths for the concretes with mineral admixtures ranged from 50 to 71 MPa compared to the portland cement concrete strength of 53 to 58 MPa. Between 4 and 7 months, the FA and slag concretes attained compressive strengths of 60 to 90 MPa compared to 60 to 70 MPa of the portland cement concrete. It is thus clear that the pozzolanic/cementitious activity of the FA/SF and Slag/SF systems contributes to continued increase in strength more than when portland cement is used alone in concrete

Prolonged exposure to air drying results in a slowing down of the strength development, and this is seen to occur to both portland cement concrete and concrete with mineral admixtures. It is interesting to note, however, that with the 350 kg/m^3 mixtures, the FA and Slag concretes developed higher strengths compared to portland cement concrete strengths, even under prolonged air drying. The former developed equivalent cube strengths of 63 to 73 MPa compared to 63 MPa of the latter. Generally, strength loss of FA and Slag concretes can be substantial when exposed to prolonged air drying. However, with an adequate and minimum portland cement content and sufficient water content, it is possible to continue the hydration process albeit at a slower rate when FA and Slag concretes are continuously exposed to a drying environment. The strength development of air-cured concrete in Table 4 supports this phenomenon. Thus the data in Table 4 suggest that up to about 30% cement replacement, FA and Slag concretes can be designed to develop strength with time although at a slower rate, provided the mixture contains an adequate amount of portland cement and water to support continued hydration and pozzolanic reactivity even in a drying environment.

This view is indirectly supported by the strength development of mixture ZY with time as shown in Table 4. At high cement replacement levels, prolonged exposure to drying will impede and slow strength development, and may even result in a reversal of strength gain with time due to cessation of pozzolanic and cementitious reactivity, but careful mixture proportioning, and an adequate w/cm, can prevent this reversal and ensure continued hydration and strength increase even when the ambient conditions are not favorable to such reactivity.

A clearer picture of the strength development with time can be seen in Table 5 which gives the strength at any age as a per cent of the 28 day strength. These data emphasize the implications to strength of moderate and large cement replacements, and of prolonged air drying. The results of Table 5 show that with adequate portland cement and water contents in the mixture, the incorporation of combinations of FA, Slag and SF in concrete can be made to bring continued strength benefits, but that very large cement replacement levels will require special considerations if their full contribution to strength is to be mobilized. In other words, a minimum portland cement content, and an adequate w/cm are essential if the benefits of cement replacement materials are to be fully utilized, when the exposure conditions are unfavorable, to strength and microstructure development.

Flexural Strength

The flexural strength properties of all the concrete mixtures investigated in this research, and exposed to the three curing conditions, are shown in Table 6. These results show in general terms similar trends to the development of compressive strength. Flexural strength, however, is much more sensitive to moisture gradients and the resulting shrinkage cracks, unlike the compressive strength, and prolonged exposure to a drying environment can cause a reduction in flexural strength. The results of Table 6 confirm this trend, and show that all the concretes exhibited this phenomenon. These data in Table 6 also show some loss in flexural strength beyond about three months' of water curing. It is not clear at the moment why this should happen, except to say that some drying has probably occurred between removal of the specimens from the water tank and testing. If this were the case, then it would seem that moisture gradients are much more critical to flexural strength properties than perhaps envisaged. Further tests are in progress to examine this aspect of the engineering properties of concretes.

Flexural - Compressive Strength Ratio

An examination of the flexural and compressive strength data in Table 6 and Table 2 to 4 show that at one day the flexural-compressive strength ratio of all FA/SF and Slag/SF concrete mixtures is higher than that of the portland cement concrete. However, with further curing, the differences in these ratios level out, and all the concretes exhibit similar ratios of flexural to compressive strength beyond 7 days. A particular trend observed again with all the concrete mixtures is that the ratio of the two strengths depends on the general level of the compressive strength of the concrete; the higher the compressive strength, the lower is the ratio of flexural to compressive strength.

Fig. 1 shows a graphical representation of the variation of flexural strength, f, with compressive strength, f_c, and time for all the concrete mixtures exposed to the three curing regimes. Regression analysis of the data gave the following equations and correlation coefficients:

$$f = 0.71\, f_c^{0.53}\ \text{(wet)}, \qquad r = 0.969 \qquad (1)$$

$$f = 0.76\, f_c^{0.51}\ \text{(wet/air)}, \qquad r = 0.966 \qquad (2)$$

$$f = 0.80\, f_c^{0.82}\ \text{(air)}, \qquad r = 0.903 \qquad (3)$$

These data imply a reasonably good correlation between flexural strength and compressive strength, for all the materials studied.

Dynamic Modulus of Elasticity

The dynamic modulus results for all the concrete mixtures and the three curing conditions used in this study are shown in Table 7. These results show that the curing regime has a much more positive and definitive effect on elastic modulus than on compressive strength. Irrespective of the type of concrete, the highest dynamic modulus was obtained under continuous wet curing, whereas the lowest values were registered under prolonged air drying. Further, these differences in dynamic modulus between wet curing and air drying were higher for the FA/SF and Slag/SF concretes compared to that of the portland cement concrete, emphasizing further the sensitivity of concretes with pozzolanic and slag admixtures to lack of adequate moist curing.

The results for the mixtures W, X, Y, and Z also emphasize further differences in elastic moduli between portland cement concretes and concretes with FA and Slag. The addition of FA and Slag with SF invariably reduces the dynamic modulus, and the higher the replacement level, the greater is the reduction. The reduction in dynamic modulus with increasing levels of cement replacement is further confirmed by the data for the mixtures ZX and ZY shown in Fig. 2.

Further, all other things being equal, the Slag replacements gives a higher dynamic modulus than the FA replacement (mixtures Y and Z). This phenomenon was also observed earlier in relation to compressive strength (Table 4), and to a lower degree, with flexural strength (Table 6). Amongst all engineering properties, the dynamic modulus is probably the more significant parameter to assess and evaluate the relative roles and effectiveness of FA and Slag in densifying the portland cement matrix. The dynamic modulus is much more sensitive to changes in microstructure than either compressive strength or flexural strength, and the results in Table 7 confirm that Slag is slightly more effective in densifying the cement matrix than FA.

Compressive Strength - Dynamic Modulus Relationship

The variation of dynamic modulus with compressive strength for all the concretes and curing conditions tested in this study is shown in Fig. 3. The regression equations relating compressive strength to dynamic modulus are as follows:

$$E = 11.46\, f_c^{0.32} \text{ (wet)}, \qquad r = 0.98 \tag{4}$$

$$E = 15.74\, f_c^{0.23} \text{ (wet/air)}, \qquad r = 0.92 \tag{5}$$

$$E = 15.81\, f_c^{0.53} \text{ (air)}, \qquad r = 0.940 \tag{6}$$

These results confirm good relationship between dynamic modulus and compressive strength for all the concretes and curing regimes investigated.

Swelling and Shrinkage

The drying shrinkage and swelling of the portland cement concrete, and the FA/SF and Slag/SF concretes are shown in Table 8. Although there are minor differences between all the concretes with continued exposure, the final shrinkage values at the end of 260 days are all of the same order, irrespective of the type of concrete, although in general, the shrinkage of FA/SF and Slag/SF concretes is marginally lower than that of portland cement concrete (Fig. 4.). The final shrinkage values of all the concretes were in the range of 550 to 650 x 10^{-6}.

The swelling strain data in Table 8 also show similar effects of FA and Slag. The swelling strains at the end of 260 days for all the concretes varied from 80 to 130 x 10^{-6}, and in general, concretes with these cementitious materials tended to show slightly higher swelling when continuously exposed to water than portland cement concrete.

Ultrasonic Pulse Velocity

The ultrasonic pulse velocity is an effective means of evaluating the quality of concrete by monitoring the properties of the different concrete mixtures with time and exposure conditions. The technique is highly sensitive to the development of internal microcracking, and will therefore be able to assess the relative influences of FA, Slag and SF in modifying the structure of portland cement concrete. Table 9 summarizes the pulse velocity values of all the concretes at various ages and curing conditions. The results show that in all curing environments the pulse velocity values of FA/SF and Slag/SF mixtures are marginally lower than that of the portland cement concrete, and that prolonged drying lowers these values with continued ageing more or less by the same amount for the two types of concretes.

Indeed, so far as the densification of the microstructure is concerned, these pulse velocity values emphasize that there is little difference between portland cement concrete and FA/SF and Slag/SF concretes.

One interesting point arising from the data shown in Table 9 is that, all things being equal, Slag/SF mixtures densify the cement matrix slightly better than the FA/SF mixtures. This is shown both by mixtures Z and ZY, and confirms the trends reported earlier that slag is marginally superior to FA in the development of the engineering properties of concrete.

CONCLUSIONS

The major conclusions derived from this study are described below.

1. With combinations of FA/SF and Slag/SF, and total cementitious contents of 350 kg/m^3 and 450 kg/m^3, one day cube strengths of 15 to 24 MPa were obtained compared to about 27 MPa with portland cement alone. In general, the one-day strength was lower, the higher the cement replacement level. The Slag/SF combinations lagged slightly behind the FA/Slag mixture in the development of one-day strength, but this tendency was reversed with continued hydration.

2. All the FA/SF and Slag/SF concretes attained 40 MPa at 7 days, except the concrete with a substantial slag content, but even then the latter achieved a strength of about 37 MPa.

3. The 28-day cube strength of the FA/SF and Slag/SF concretes ranged from 50 to 71 MPa compared to the portland cement concrete strength of 53 to 58 MPa. Between 4 and 7 months FA and Slag concrete mixtures reached 60 to 90 MPa, compared to 60 to 70 MPa of the concrete with portland cement alone.

4. Prolonged exposure to air drying slows down the strength development of all concretes, irrespective of whether they contain FA/Slag/SF, or not. Upto about 30% cement replacement level, FA and Slag concrete mixtures can be proportioned to develop strength increase with time, albeit at a slower rate, and even when the exposure conditions are not favorable to such reactivity, provided the mixtures contained an adequate amount of portland cement and water to continue the pozzolanic/hydration reactivity.

5. The flexural strength development generally follows that of compressive strength. However, unlike compressive strength, flexural strength is much more sensitive to moisture gradients and the resulting shrinkage microcracking, and prolonged air drying caused a reduction in flexural strength in all concretes.

6. All the concretes showed similar flexural-compressive strength ratios in the long-term, with the general trend of a lower ratio, the higher the compressive strength. Regression analysis showed a good correlation between flexural strength and compressive strength.

7. The curing conditions have a much more definitive effect on dynamic modulus than on compressive strength. Continuous exposure to humid conditions maintained high values of dynamic modulus, and the differences in dynamic modulus between wet curing and air drying were higher for FA/SF and Slag/SF concretes than portland cement concretes, emphasizing the sensitivity of FA and Slag concretes to lack or cessation of moist curing.

8. In general, the higher the cement replacement level, the greater was the reduction in dynamic modulus of FA/SF and Slag/SF concretes. Similarly, as for compressive strength, slag replacement resulted in a slightly higher elastic modulus compared to FA replacement. By implication, slag replacement appears to be more effective in densifying the cement matrix than FA.

9. There was a good correlation between dynamic modulus and compressive strength for all the concretes and all the exposure conditions.

10. There was not much difference in drying shrinkage or swelling strain between normal concretes and FA and Slag concretes. FA/SF and Slag/SF concretes showed marginally lower drying shrinkage and slightly higher swelling strain when exposed to prolonged wet curing or air drying.

11. As with dynamic modulus and flexural strength, pulse velocity values are also similarly influenced by curing conditions. There was little difference in the development of the microstructure between portland cement concrete and FA/SF, Slag/SF mixtures. However, slag appeared to slightly better in the densification of the microstructure than FA.

12. The overall conclusion of replacing portland cement with FA/SF and Slag/SF mixtures is that at replacement levels up to about 30%, the

incorporation of FA, Slag and SF can produce concrete with equal or better properties than those of the portland cement concrete.

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TABLE 1—CONCRETE MIX PROPORTIONS,KG/M^3

Mix	Cement OPC	Silica fume	Fly ash	GGBFS	Water	Fine aggregate	Coarse aggregate	Superplasticiser *
W	350	-	-	-	157.5	600	1225	1.2
X	300	20	30	-	157.5	600	1225	1.2 - 1.5
Y	250	20	80	-	157.5	600	1225	1.2 - 1.5
Z	250	20	-	80	157.5	600	1225	1.2 - 1.5
ZX	300	25	-	125	202.5	600	1225	0.60
ZY	250	35	-	165	202.5	600	1225	0.68

* superplasticiser:weight % of cementitious contet.

replacement levels:

mixes X,Y,Z & ZX = 6 % SF and for mix ZY = 8 % SF

mix X = 9 % FA and mix Y = 23 % FA

mix Z = 23 % slag, mix ZX = 28 % slag and mix ZY =37 % slag

TABLE 2—COMPRESSIVE STRENGTH DEVELOPMENT OF FA/SF CONCRETE AT EARLY AGES

Concrete mixes, kg/m^3	Age, days	Compressive strength, MPa	Percentage of 28 day strength
350 OPC	1	27.3	49
(W)	7	47.5	85
300 OPC+20 SF+30 FA	1	24.0	40
(X)	7	45.7	76
250 OPC+20 SF+80 FA	1	18.1	30
(Y)	7	40.8	69

TABLE 3—COMPRESSIVE STRENGTH DEVELOPMENT OF SLAG/SF CONCRETE AT EARLY AGES

Concrete mixes, kg/m^3	Age, days	Compressive Strength, MPa	Percentage of 28 day strength
350 OPC	1	27.3	49
(W)	7	47.5	85
250 OPC+20 SF+80 slag	1	15.6	23
(Z)	7	48.6	70
300 OPC+25 SF+125 slag	1	16.7	27
(ZX)	7	39.6	64
300 OPC+35 SF+165 slag	1	9.6	16
(ZY)	7	36.6	60

TABLE 4—LONG TERM COMPRESSIVE STRENGTH DEVELOPMENT OF FA/SF AND SLAG/SF CONCRETE

Mix type, kg/m^3	Age, days	Compressive Strength, MPa		
		Wet	7d wet / air	Air
350 OPC (W)	28	55.7	57.9	52.9
	90	60.8	63.2	59.6
	260	68.5	71.5	62.2
300 OPC + 20 SF + 30 FA (X)	28	60.1	63.6	60.1
	90	75.5	77.3	71.1
	260	78.3	80.1	73.0
250 OPC + 20 SF + 80 FA (Y)	28	59.4	64.0	57.1
	90	67.8	72.7	61.0
	260	71.4	76.2	63.0
250 OPC + 20 SF + 80 Slag (Z)	28	67.9	70.9	61.7
	90	74.8	78.4	67.5
	260	84.8	88.0	70.1
300 OPC+25 SF+125 Slag (ZX)	28	-	62.1	48.6
250 OPC+35 SF+165 slag (ZY)	28	61.6	61.0	44.4
	120	69.7	72.1	52.0

TABLE 5—COMPRESSIVE STRENGTH DEVELOPMENT EXPRESSED AS A PERCENTAGE OF 28 DAY STRENGTH OF CONTROL CONCRETE, W

Curing condition	Age, day	Percentage of 28 day strength, %					
		W	X	Y	Z	ZX	ZY
Wet curing	1	49	43	32	28	-	17
	7	85	82	73	87	-	66
	28	100	108	107	122	-	110
	90	109	135	122	134	-	125
	260	123	141	128	152	-	-
7d wet / air curing	1	47	41	31	27	29	17
	7	83	76	71	84	68	63
	28	100	110	111	123	107	105
	90	109	133	126	135	-	124
	260	124	138	132	152	-	-
Air curing	1	52	45	34	29	32	18
	7	88	85	76	88	73	68
	28	100	114	108	117	92	84
	90	113	134	115	128	-	98
	260	118	138	119	132	-	-

TABLE 6—FLEXURAL STRENGTH OF ALL CONCRETE MIXTURES UNDER VARIOUS CURING CONDITIONS

Mix type, kg/m^3	Curing Age,day	Flexural strength, MPa			Percentage of 28 day strength, %		
		wet	7d wet / air	air	wet	7d wet /air	air
350 OPC	1	3.73	3.73	3.73	61	64	82
(W)	7	5.60	5.80	3.98	92	100	87
	28	6.10	5.82	4.56	100	100	100
	90	6.16	6.84	6.22	101	118	136
	260	6.00	6.64	5.80	98	114	127
300 OPC	1	3.75	3.75	3.75	50	59	72
+20 SF	7	5.44	5.32	4.74	73	84	90
+30 FA	28	7.42	6.30	5.24	100	100	100
(X)	90	7.30	7.78	7.00	98	123	134
	260	6.8	6.9	6.20	92	110	118
250 OPC	1	3.28	3.28	3.28	61	53	62
+20 SF	7	4.64	4.66	4.28	86	75	81
+80 FA	28	5.42	6.18	5.26	100	100	100
(Y)	90	6.74	6.86	6.04	124	111	115
	260	6.56	6.30	5.30	121	102	100
250 OPC	1	2.97	2.97	2.97	49	52	55
+20 SF	7	5.36	5.08	4.34	89	88	81
+80 Slag	28	6.02	5.76	5.36	100	100	100
(Z)	90	8.50	8.32	8.02	141	144	150
	260	6.88	6.14	5.08	114	107	95
300 OPC	1	-	3.31	3.31	-	58	71
+25 SF	7	-	4.94	3.72	-	86	80
+125 Slag (ZX)	28	-	5.74	4.66	-	100	100
250 OPC	1	2.36	2.36	2.36	28	42	58
+35 SF	7	5.24	5.24	3.62	62	92	88
+165 Slag	28	8.48	5.68	4.10	100	100	100
(ZY)	120	7.32	-	4.56	86	-	111

TABLE 7—DEVELOPMENT OF DYNAMIC MODULUS OF ELASTICITY WITH AGE

Mix type	curing condition	Compressive strength MPa (28-day)	Dynamic modulus GPa (28-day)	Compressive strength MPa (90-day)	Dynamic modulus GPa (90-day)	Compressive strength MPa (260-day)	Dynamic modulus GPa (260-day)
W	Wet curing	55.7	42.8	60.8	44.6	68.5	46.0
X		60.1	42.1	75.5	44.0	78.3	45.3
Y		59.4	41.0	67.8	43.0	71.4	44.4
Z		67.9	42.7	74.8	44.6	84.8	45.7
ZY		61.6	44.0	69.7	47.2	-	-
W	7d wet/air curing	57.9	42.8	63.2	43.3	71.5	43.6
X		63.6	39.7	77.3	39.8	80.1	39.3
Y		64	38.6	72.7	38.7	76.2	38.3
Z		70.9	40.4	78.4	40.8	88.0	40.0
ZX		62.1	41.1	-	-	-	-
ZY		61.0	40.1	72.1	-	-	-
W	air curing	52.9	40.1	59.6	40.4	62.2	40.8
X		60.1	38.1	71.1	38.2	73.0	38.1
Y		57.1	36.3	61.0	36.5	63.0	36.6
Z		61.7	37.9	67.5	38.6	70.1	38.1
ZX		48.6	37.7	-	-	-	-
ZY		44.4	36.2	52.0	38.2	-	-

TABLE 8—SHRINKING AND SWELLING OF FA/SF AND SLAG/SF CONCRETES

Mix type	Type of curing	Shrinkage, microstrains				Percentage of 260 day shrinkage		
		7 days	28 days	90 days	260 days	7 days	28 days	90 days
W	7d wet / air curing	134	239	423	594	25	45	70
X		178	319	444	574			
Y		191	388	499	610	TO	TO	TO
Z		193	311	421	549			
ZX		127	301	-	-			
ZY		158	313	-	-	40	70	80
W	Air curing	135	321	484	657	20	50	70
X		177	384	494	615			
Y		170	432	530	647	TO	TO	TO
Z		179	380	473	599			
ZX		130	341	-	-			
ZY		161	332	-	-			80
W	Wet curing (Swelling)	-34	-76	-79	-90	10	30	100
X		-14	-44	-64	-83			
Y		-14	-43	-84	-113	TO	TO	TO
Z			-68	-87	-99			
ZY		-55	-86	-120	-130	40	60	110

TABLE 9—PULE VELOCITY OF FA/SF AND SLAG/SF CONCRETES, KM/S

Curing condition	Mixes / Age, day	W	X	Y	Z	ZX	ZY
Wet curing	1	4.20	4.05	3.95	3.90	-	3.71
	7	4.46	4.42	4.40	4.45	-	4.42
	28	4.58	4.57	4.58	4.45	-	4.69
	90	4.66	4.64	4.63	4.67	-	4.73
	260	4.72	4.68	4.66	4.71	-	-
7d wet / air curing	1	4.20	4.05	3.96	3.90	3.81	3.68
	7	4.50	4.41	4.40	4.45	4.43	4.39
	28	4.6	4.53	4.50	4.61	4.59	4.57
	90	4.6	4.44	4.50	4.63	-	-
	260	4.6	4.46	4.45	4.51	-	-
Air curing	1	4.22	4.09	3.97	3.90	3.83	3.67
	7	4.46	4.36	4.26	4.33	4.28	4.20
	28	4.55	4.49	4.41	4.51	4.46	4.39
	90	4.54	4.50	4.41	4.54	-	4.43
	260	4.50	4.39	4.35	4.42	-	-

Fig. 1—Relation between flexural strength and compressive strength

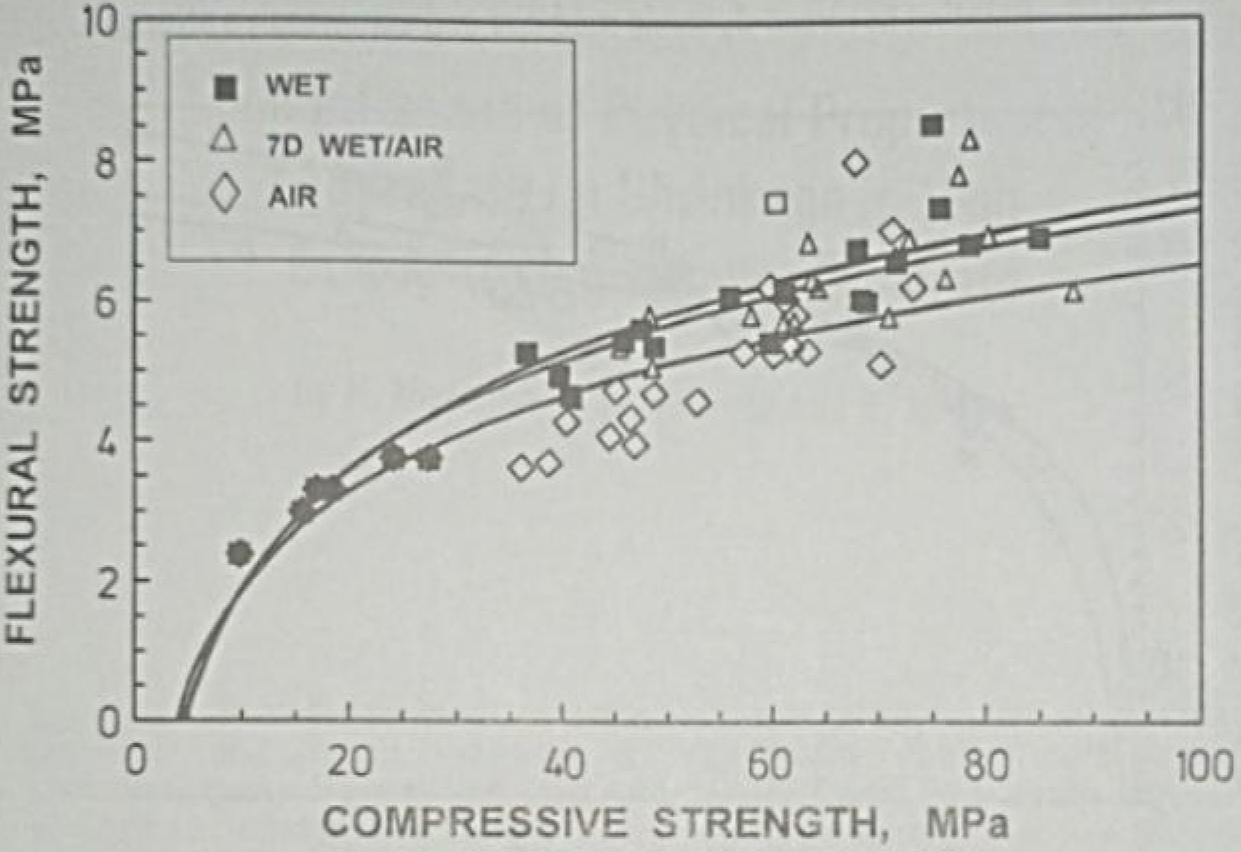

Fig. 2—Dynamic modulus for mixtures ZX and ZY

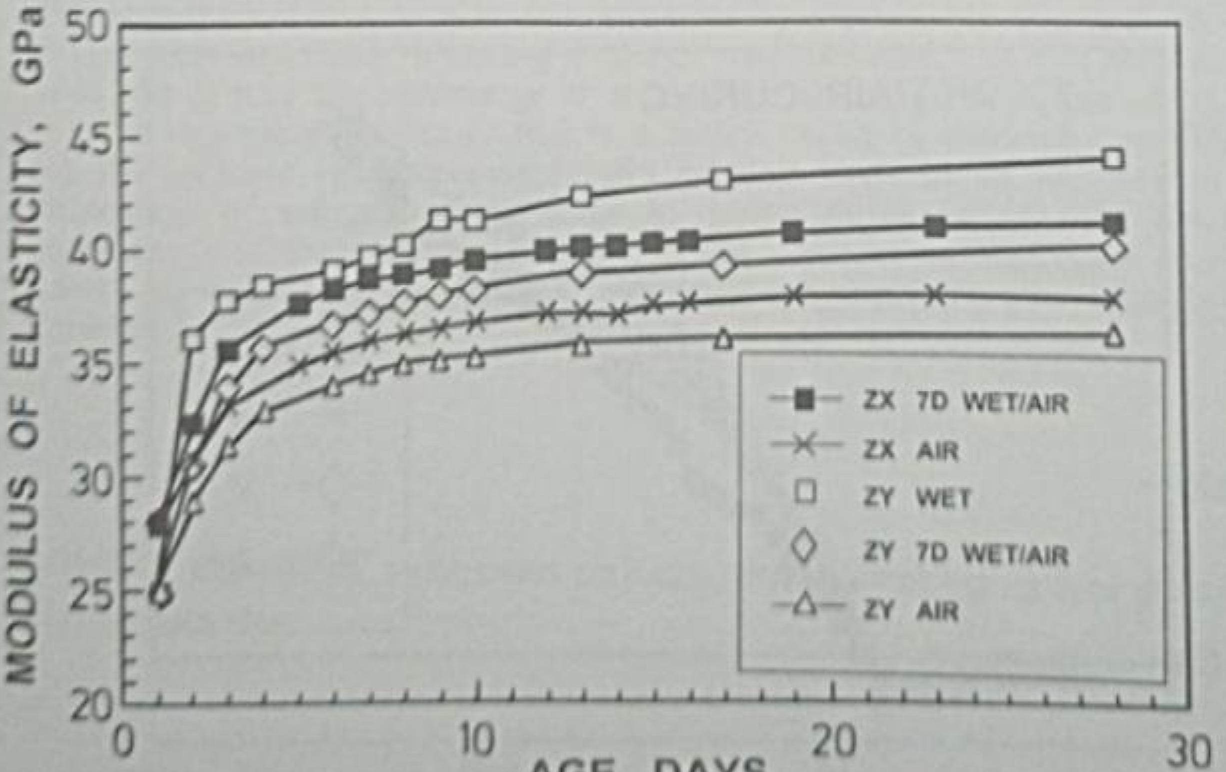

Fig. 3—Relation between dynamic modulus and compressive strength

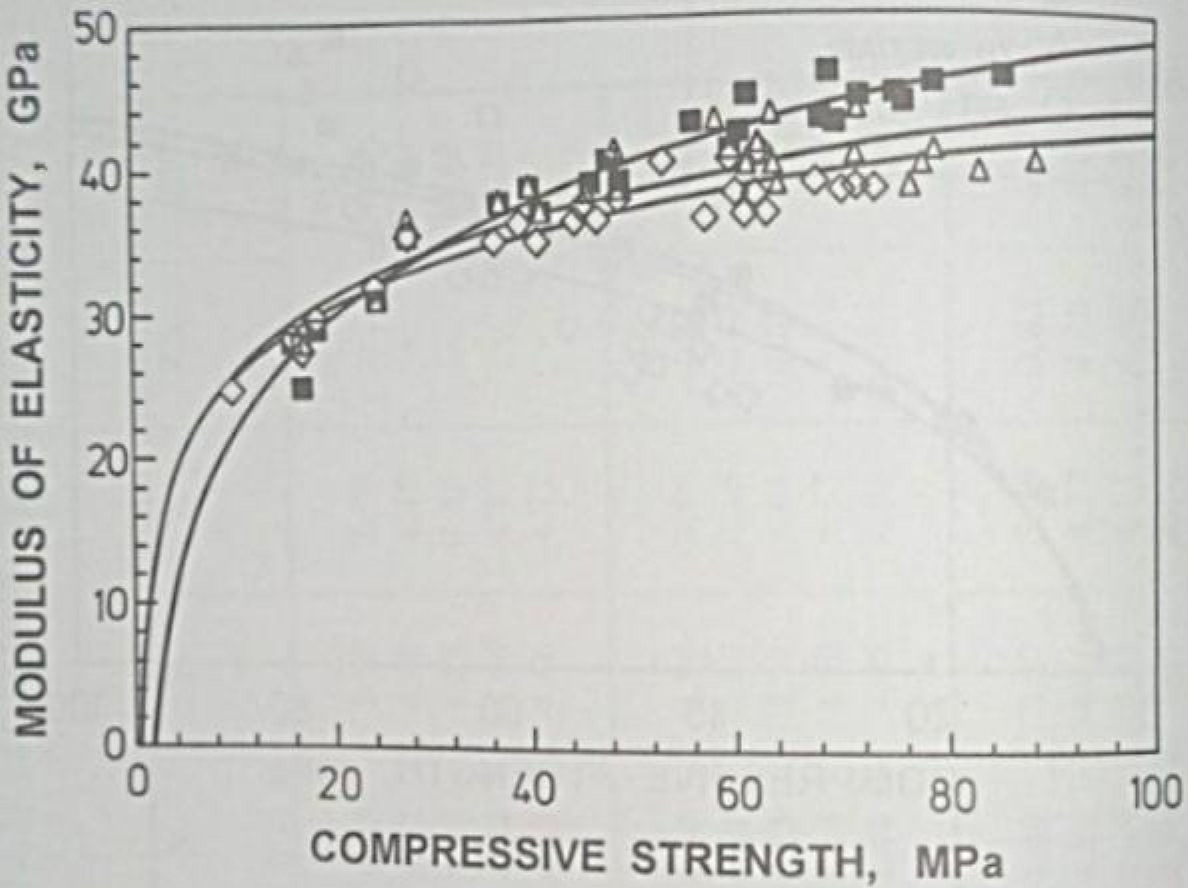

Fig. 4—Shrinkage of FA/SF and SLAG/SF concretes