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EFFECT OF COARSE AGGREGATE ON ELASTIC MODULUS AND COMPRESSIVE STRENGTH OF HIGH PERFORMANCE CONCRETE

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ABSTRACT

A set of high performance concrete mixes, of low water/cement ratio and fixed mortar composition, containing six different types of aggregates of constant volume fraction, has been used to check moduli of elasticity at 7, 28 and 91 days. The results have shown that, apart from the aggregates of very low and very high modulus, concrete modulus at 28 days can be predicted quite well by well-known models. Increase in modulus thereafter is slight. Cube strength (about 90 N/mm^2 at 28 days with normal aggregates) is drastically reduced, as expected, by the weaker aggregates and is also reduced (by about 9%) by the stiffer (steel) aggregates.

Introduction

From the point of view of the design and behaviour of structures, not only compressive strength but modulus of elasticity is also important. With the rapid advance of concrete technology, compressive strength over 100 MPa can be readily produced using conventional materials and production methods (1). Modulus, however, increases to a much less extent than strength. For instance, while strength increases from 50 MPa to 100 MPa, modulus may be enhanced only about 20% using the same aggregate type and content. Furthermore, to make best use of strength potential, structures of high strength concrete tend to be slimmer and require higher modulus. Therefore, knowledge of the modulus of high strength concrete is very important in avoiding excessive deformations and providing satisfactory serviceability of structures.

With a wide range of coarse aggregates available for high performance concrete (from lightweight to normal weight), and recognising their important role in affecting both strength and modulus (2-4), it is wise to extend their study into the less established region beyond that normally used in design.

Many researchers have set up theoretical models for prediction of relationships between modulus of concrete and moduli of its constituents. As far as the effect of aggregate is concerned, concrete may be treated as a simplified two-component composite: cement mortar and coarse aggregate. Modulus of concrete is thus related to moduli of cement mortar and coarse aggregate, and bond between them. In the present study, some models are compared with experimental results to check their applicability to high performance concrete with a wide range of coarse aggregate types. In this context high performance is linked to cement mortar of high quality (i.e. of low water/cement ratio), even though, for purposes of studying E values, the coarse aggregate used may limit the concrete strength to rather low values.

Experimental

Aggregates

In the experimental programme, a wide range of coarse aggregate types, from very soft to extremely stiff, was included, some properties of which are given in Table 1.

TABLE 1
Properties of Coarse Aggregates Used

Aggregate	Relative density (oven-dry)	Shape	Maximum size (mm)	24-hour Water absorption (% of dry mass)
Expanded clay	0.80	spherical*	10	17.5
Sintered fly ash	1.52	spherical	6	13.6
Limestone	2.64	angular	10	2
Gravel	2.57	rounded	10	2
Glass	2.52	spherical	10	0
Steel	7.85	spherical	3	0

*mixed broken and unbroken particles.

Mix Proportions

The mix proportions are given in Table 2. Six concretes with different aggregates and one mortar were cast. In all the concrete mixes the amounts of cement, silica fume, sand and free water were the same. The mass of coarse aggregate was adjusted for each mix to keep the same volume fraction (0.425). For the mortar, the proportions of cement, silica fume sand and free water were the same as in concrete mixes.

Water-binder ratio (W/(C+S)) was 0.29 and silica fume replacement rate (S/(C+S)) was 10%. The active ingredient amount of the superplasticizer changed from 0.5% to 1% of cement and silica fume content to maintain appropriate workability for different concretes.

Silica fume was in the form of slurry of 50% concentration. Superplasticizer was Complast 430, of sulfonated naphthalene formaldehyde type.

TABLE 2
Concrete Mixes. (W/C+S=0.29, S/C+S=10%)

Material	Content (kg/m^3)	Volume fraction* (%)
Cement (class 42.5 N)	443	14.2
Silica fume	49	2.0
Water (free)	143	14.3
Sand	660	24.4
Coarse aggregate		
Expanded clay	340	
Sintered fly ash	646	
Crushed limestone	1105	42.5
Gravel	1105	
Glass bead	1071	
Steel bead	3357	

*assuming about 2.5% air content

Specimen preparation

In mixing, cement, sand and coarse aggregate were generally blended first and silica fume, superplasticizer and water were then added. The lightweight aggregates were first mixed (with enough water for the short-term absorption for half an hour) before blending with cement and sand. Three cubes (100 mm for mortar, gravel and crushed limestone and 76 mm for others) and two or three prisms (76*76*254 mm) were cast for each mix. All the specimens were stored in water at $20^o C$ until tested.

Measurements

Compressive strength was generally measured at 28 days although some cubes were tested at 7 or 91 days. Electro-dynamic modulus was determined by the longitudinal resonant frequency method (British Standard BS 1881) at 7, 28 , 56 and 91 days. In addition, ultrasound pulse velocity was also determined at 7, 28 and 56 days.

Theoretical Models

As with simple springs and dashpots in rheological models, many composite models can be derived for concrete by different combinations of mortar and aggregate elements (see Fig. 1), thus yielding modui related to the structure.

Let E_c, E_m and E_a denote moduli of concrete, cement mortar and coarse aggregate respectively. If volume fraction of coarse aggregate is V_a, then volume fraction of cement mortar can be assumed to be $1-V_a$.

If cement mortar and aggregate are assumed to be coupled in parallel, as Voigt's model (5) (Fig. 1.a), modulus of concrete can be expressed as follows:

$$\frac{E_c}{E_m} = 1 + (\frac{E_a}{E_m} - 1)V_a.$$

On the other hand, if mortar and aggregate are coupled in series, then Reuss' model (5) (Fig. 1.b) is obtained as follows:

$$\frac{E_m}{E_c} = 1 + (\frac{E_m}{E_a} - 1)V_a$$

Combining Voigt's and Reuss' model, gives Hirsch's model (6) (Fig. 1.c):

$$\frac{E_m}{E_c} = \frac{1}{2}\left(\frac{1}{1+(\frac{E_a}{E_m}-1)} + (1 + (\frac{E_m}{E_a} - 1))\right)$$

More realistic models are illustrated in Fig. 1(d) and 1(e). The model shown in Fig. 1(d) is the original Counto model (7), which is as follows:

$$\frac{E_c}{E_m} = 1 + \frac{V_a}{\sqrt{V_a} - V_a + \frac{E_m}{E_a - E_m}}$$

As in Fig. 1(e) another version of Counto's model is given as follows:

$$\frac{E_c}{E_m} = 1 + \frac{V_a}{\frac{E_a}{E_a - E_m} - \sqrt{V_a}}$$

Based on the Bache and Nepper-Christensen's model (BNC) (8) for strength, a simple model has been proposed (9), by analogy, as follows:

$$\frac{E_c}{E_m} = (\frac{E_a}{E_m})^{V_a}$$

This model, contrary to other models, has no physical reality.

Results and Discussion

Modulus of elasticity

The measured moduli of mortar and concretes with different aggregates are shown in Table 3 and Fig. 2. With lightweight aggregates, concrete has, as expected, a lower modulus than mortar. Strong aggregates, on the other hand, naturally produce concrete with higher modulus than mortar. Self-evidently, therefore, coarse aggregates of such different stiffnesses can have great effects on the modulus of high performance concrete.

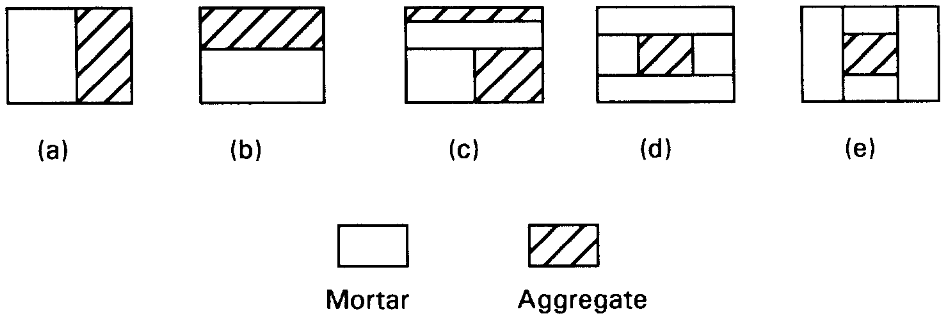

FIG.1
Illustration of Composite Models

TABLE 3
Measured Dynamic Modulus and Compressive Strength of Cement Mortar and Concretes at Varying Ages

Material type	Nominal Density (kg/m^3)	Measured dynamic modulus (GPa) at age (day)				Compressive strength (MPa) at age (day)		
	28 days	7	28	56	91	7	28	91
Mortar	2290	38.0	40.8	41.3	41.5	70	91	
Expanded clay	1540	17.9	18.6	18.8	18.9		28	29
Sintered fly ash	1990	28.8	30.2	30.6	30.8		74	77
Limestone	2430	46.6	49.5	50.0	50.3	68	91	
Gravel	2460	48.8	51.3	51.6	51.7	68	88	
Glass	2390	51.2	52.8	53.1	53.4		96	105
Steel	4620	66.8	69.9	70.4	70.9		83	

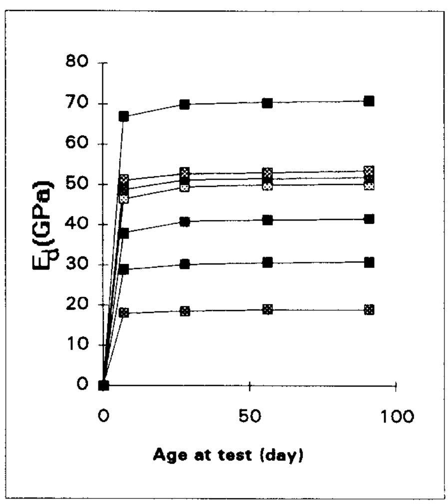

FIG. 2
Modulus of Elasticity E_d(GPa) of Concretes at Different Ages

The modulus of elasticity at 7 days is about 94% of that at 28 days with very small increases thereafter.

Table 4 gives moduli of aggregates, mortar and concrete together with the theoretical predictions of modulus of concrete. Except for glass and steel the moduli for which were found in the literature (10), moduli of other aggregates were calculated from a relationship between density and modulus given by Muller-Rochholz (11) in the form of:

$$E_a = 8.1 * \rho_a^2$$

where ρ_a is density of aggregate.

TABLE 4
Comparison between Experimental and Theoretical Moduli Predicted by Different Models.

Matérial	Modulus of Aggregate (GPa)	Measured Ed (GPa) at 28 days	Theoretical Ed (GPa) Estimated from different models					
			Voigt	Reuss	Hirsch	Counto	PCounto	BNC
Mortar		40.8						
Expanded clay	5.2	18.6	26.1	12.0	16.4	21.9	19.1	17.0
Sintered fly ash	18.2	30.2	31.3	26.9	28.9	29.8	28.9	29.0
Limestone	56	49.5	47.2	46.1	46.6	46.8	46.5	46.5
Gravel	54	51.3	46.4	45.5	45.9	46.0	45.8	46.0
Glass	72	52.8	54.0	50.0	51.9	52.1	51.3	51.9
Steel	210	69.9	112.8	62.0	80.0	77.8	70.2	81.5

Generally speaking, the modulus of concrete should lie between the predictions by Voigt's and Reuss' models which usually give upper and lower bounds respectively. As can be seen from Table 4, moduli of concrete with gravel and limestone are greater than the predictions of Voigt's model. It may be that the estimated modulus for gravel and limestone are rather low.

Compared to the experimental results, all models give results within less than 10% of experimental values except for expanded clay and steel bead, (see Fig. 3). In view of the whole range of aggregates, all models except for Voigt's and Reuss give quite similar results, but the parallel version of Counto's model agrees best with the experiments. The simple model based on the Bache, Nepper-Christensen analogy is sufficiently accurate for most concretes.

Compressive Strength

Compressive strength of cement mortar and concretes at 7, 28 or 91 days are given in Table 3. Fig. 4 illustrates the effect of aggregates on strength at 28 days.

While it is not easy to link, directly, aggregate strength to concrete strength (although different aggregates can affect the 'ceiling strength' of the concrete) very porous

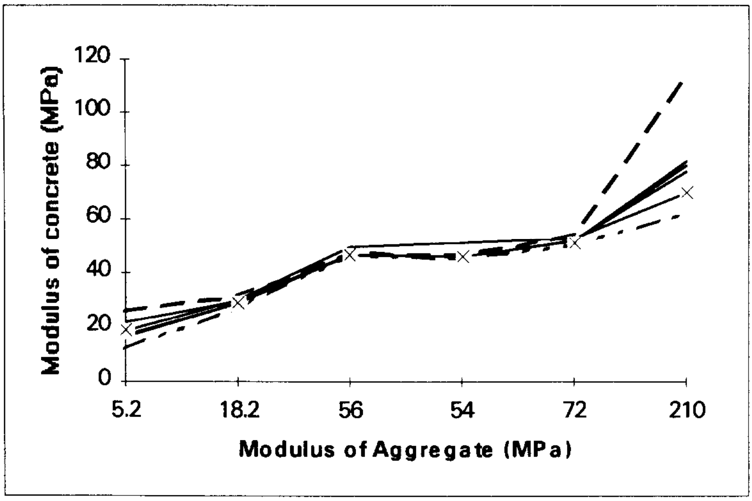

FIG. 3
Comparisons between Theoretical Predictions by the Models and Experimental Results for 28-day Old Prisms. (See TABLE 4)

particles will have a reducing effect. For example the concrete containing the expanded clay aggregates has a 28-day cube strength of about 30% of that of the mortar; the corresponding value for the sintered fly ash aggregates is about 80%. The limestone aggregate produces concrete of the same strength as the mortar although it is unlikely to be always so. Surprisingly, the measued cube strength is high for glass bead and this may be a reflexion of the insensitivity of the cube strength to aggregate-mortar bond failure, which is certainly evident in this type of concrete. Probably tensile testing would rank these concretes in a different order.

Steel bead gives rise to lower strength than that of mortar, which may be partly attributed to bond and partly to high difference between moduli of aggregate and mortar. Too stiff an aggregate, though improving modulus, may cause stress

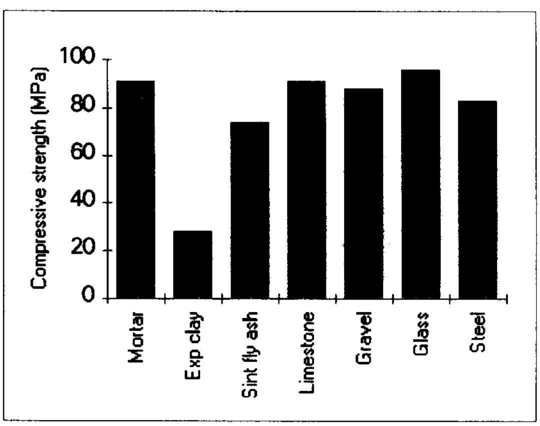

FIG. 4
Effect of Aggregates on Compressive Strength of Concrete (28 days old at test)

concentrations and initiate more microcracking causing a decrease in strength. From observation, almost all the cracks in the concrete went through the aggregates except for glass beads where a small number of aggregates were broken, and steel beads, where cracks passed around the particles.

Pulse velocity and Poisson's ratio

Ultrasound pulse velocity is useful, here, insofar as it reflects the concrete modulus; since

$$V = \sqrt{\frac{E}{\rho}}K$$

where ρ is concrete density and K is a function of Poisson's ratio, for a given concrete of more or less constant density, changes in E should be reflected in changes in V. But with large changes in density general correlation should sensibly take density into account. Thus E is likely to be related to $V^2\rho$ and, using 28-day density, E values and pulse velocity values from Tables 3 and 5 show this to be the case.

Values of Poisson's ratio calculated from the relation

$$V = \sqrt{\frac{E}{\rho}\frac{(1-\mu)}{(1+\mu)(1-2\mu)}}$$

are not generally realistic as seen in Table 5.

In principle V could be expected to correlate with strength since ρ is related to water/cement ratio and degree of hydration. But E has also an influential role, as does moisture content. With standard water curing and a fixed volume fraction of coarse

TABLE 5
Measured Ultrasound Pulse Velocity and Poisson's Ratio of Mortar and Concrete at Varying Ages

Material	Ultrasound Pulse velocity (km/s) at age (day)			Poisson's ratio at varying age (day)		
	7	28	56	7	28	56
Mortar	4.33	4.48	4.49	0.21	0.21	0.21
Expanded clay	3.80	3.96	4.01	0.27	0.29	0.29
Sintered fly ash	4.17	4.28	4.28	0.25	0.26	0.25
Limestone	4.95	5.07	5.07	0.28	0.27	0.27
Gravel	4.70	4.82	4.85	0.20	0.21	0.21
Glass	5.07	5.15	5.15	0.25	0.25	0.25
Steel	4.33	4.39	4.39	0.29	0.28	0.27

aggregates the latter parameters are constant so there is a general correlation between cube strength and pulse velocity for concrete as seen in Figure 5.

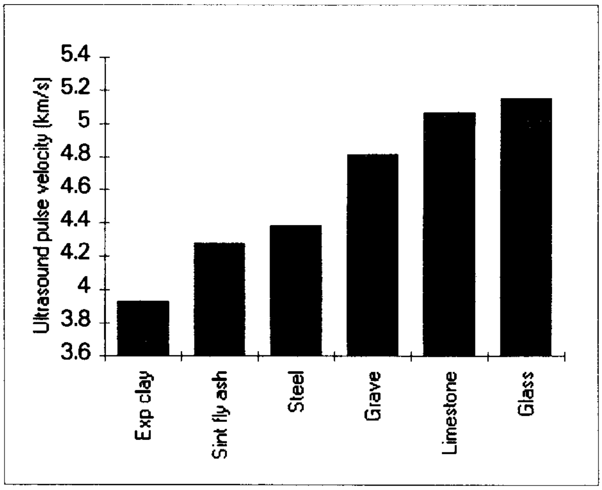

FIG. 5
Pulse Velocity of Various Concretes at 28 days in the Order of Compressive Strength.

Conclusions

For the wide range of coarse aggregate stiffness used, combined with a single, high strength, low water/cement ratio mortar, the following conclusions may be drawn:

1. As expected, coarse aggregate modulus was reflected in concrete modulus. The latter attained about 95% of its 28-day value by 7 days and gained little at later ages.

2. For mortar with modulus of about 41 GPa, concrete with normal aggregates and 28-day strength of 90 MPa had a modulus of about 50 GPa; the maximum modulus of lightweight concrete of similar composition (and strength of 74 MPa) is likely to be about 32 GPa. But the limiting value for the lowest density concrete (ceiling strength about 30 MPa) is likely to be about 20 GPa.

3. Apart from the aggregates of the lowest and highest stiffnesses, E values of concrete were predicted quite well by the models used. Poisson's ratio was not well predicted from the ultrasound pulse velocity.

4. Cube strength was affected by aggregate type; there was a major reduction when the most porous aggregate was used and there was some evidence that some reduction occurred with the stiffest aggregate.

Acknowledgements

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