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II

Effect of Aggregate Properties on the Strength and Deformation of Concrete

L'influence des caractéristiques des agrégats sur la résistance à la compression et à la déformation du béton

Der Einfluß der Eigenschaften der Zuschlagstoffe auf die Druckfestigkeit und die Formänderung des Betons

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Introduction

The effect of aggregate properties on the strength and deformation of concrete is of particular importance in prestressed concrete, since it influences the ultimate flexural capacity, the loss of prestress, and the camber and deflection of members. It also has implications for continuous reinforced concrete structures as it affects the distribution of moments and the rotation capacity of members. Previous work by Troxell, Raphael and Davis[1], Kaplan[2], and Kordina[3] has investigated the effect of aggregate properties on deformation and strength independently. In this study a direct comparison is made, the influence on workability is taken into account, and comparative tests of prestressed concrete beams are reported.

Details of Investigations

a) In the first series[4,5], compressive strength and sustained loading tests were carried out on concrete made from four types of aggregate available in Thailand. These were limestone, sandstone, andesite, and gravel. The selection was based on availability in Thailand, extent of use and uniformity of supply. Natural river sand was used as fine aggregate and the cement was Type I Normal Portland (Elephant Brand) manufactured by the Siam Cement Co. The mix proportions by weight for all specimens were: water-cement ratio 0.5; aggregate-cement ratio 4.0; sand-aggregate ratio 2/3. In order to allow a precise determination of the water content of the mixes, the aggregate was used throughout these tests in an initially dry condition. Nine 150 x 300 mm. cylinders of each mix were tested at 28 days for compressive strength. In the creep tests, 100 x 300 mm. cylinder specimens were loaded at an age of 40 days over a period of 40 days at stresses of 6.9 and 13.8 N/mm^2 under conditions of 21°C and 70% R.H. Deformations were measured along three 200 mm. gauge lengths at 120° about the axis by means of a Demec gauge. The results of these tests are summarised in Table I and Fig. 1.

Table I

Type of Aggregate	Source	Density of Concrete (gm/cc)	Cylinder Strength (N/mm^2)	Aggregate Absorption Capacity (%)	Slump* (mm)
Limestone	Rajburi	2.40	35.1	0.63	89
Sandstone	Korat	2.32	39.2	4.52	13
Andesite	Saraburi	2.42	37.6	1.46	76
Gravel	Rajburi	2.37	34.1	1.33	200

*Measured on Standard 300 mm. slump cone.

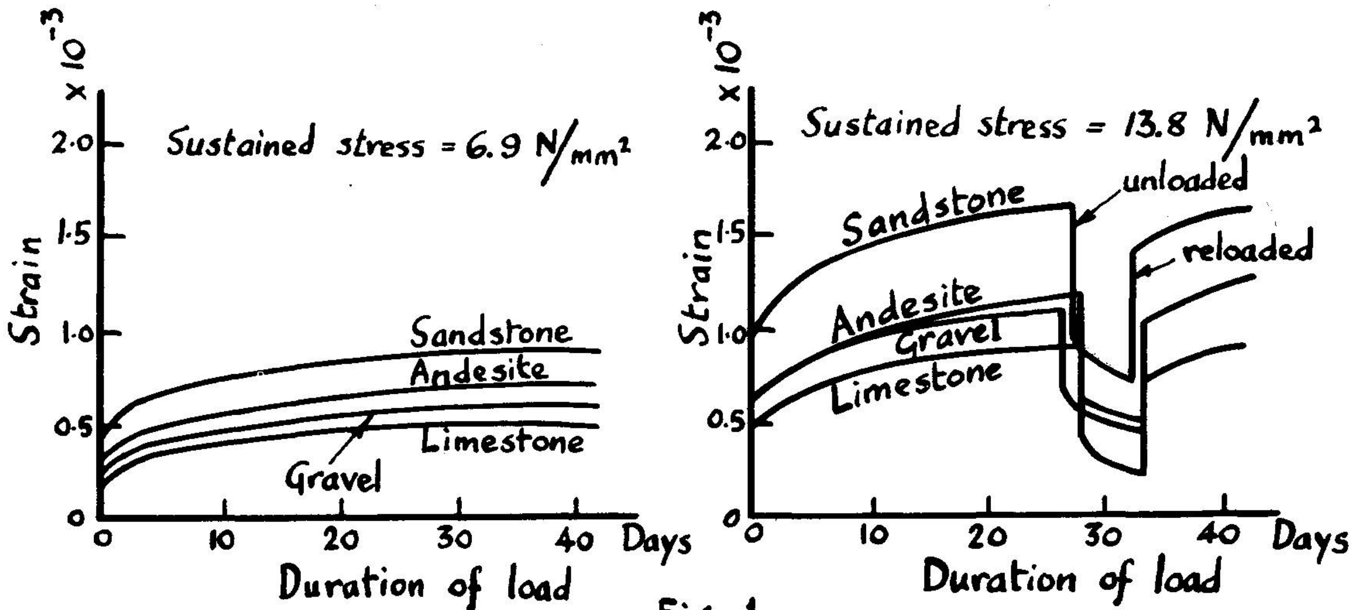

Fig. 1

b) The remaining tests were concerned with the two aggregates giving the most marked contrast in the first series, i.e. limestone and sandstone. As a preliminary, mixes of aggregate ratio as before but with four different water cement ratios were prepared using the above two aggregates, and the resulting workability and compressive strength at 7 days were investigated as given in Table II. From these tests the effect of the high absorption capacity of the sandstone is evident in reducing the effective water-cement ratio of the matrix, with consequent increase of strength and reduction of workability. From this work it was possible to design mixes for the second series of relative strength and deformation tests which had the same workability and mix proportions for limestone and sandstone aggregates but differing water-cement ratios to allow for this.

c) The second series of tests was carried out in a similar manner to that in a), except that only limestone and sandstone aggregates were used, with water-cement ratios of 0.375 and 0.475 respectively, and four different stress levels were used for the creep tests. The compression tests and the start of the sustained load tests were at an age of 7 days. The results are summarised in Table III and Fig. 2.

Table II

W/C	Aggregate	Slump	Compacting Factor	VB secs.	Density gm/cc	Comp.strength N/mm^2
0.50	Limestone	89	0.965	2	2.44	31.5
	Sandstone	13	0.827	7	2.29	33.2
0.40	Limestone	70	0.950	3	2.46	36.5
	Sandstone	8	0.824	8	2.32	37.3
0.35	Limestone	0	0.750	12	2.47	47.2
	Sandstone	0	0.694	75	2.33	48.9
0.325	Limestone	0	0.700	30	2.49	40.8
	Sandstone	0	0.684	180	2.22	19.5

Table III

Type of Aggregate	Density of Concrete (gm/cc)	Cylinder Strength (N/mm^2)	Compacting Factor	VB secs.	Aggregate Absorption Capacity(%)	Specific Gravity
Limestone	2.45	39.8	0.73	10	0.80	2.65
Sandstone	2.32	43.0	0.73	10	4.38	2.275

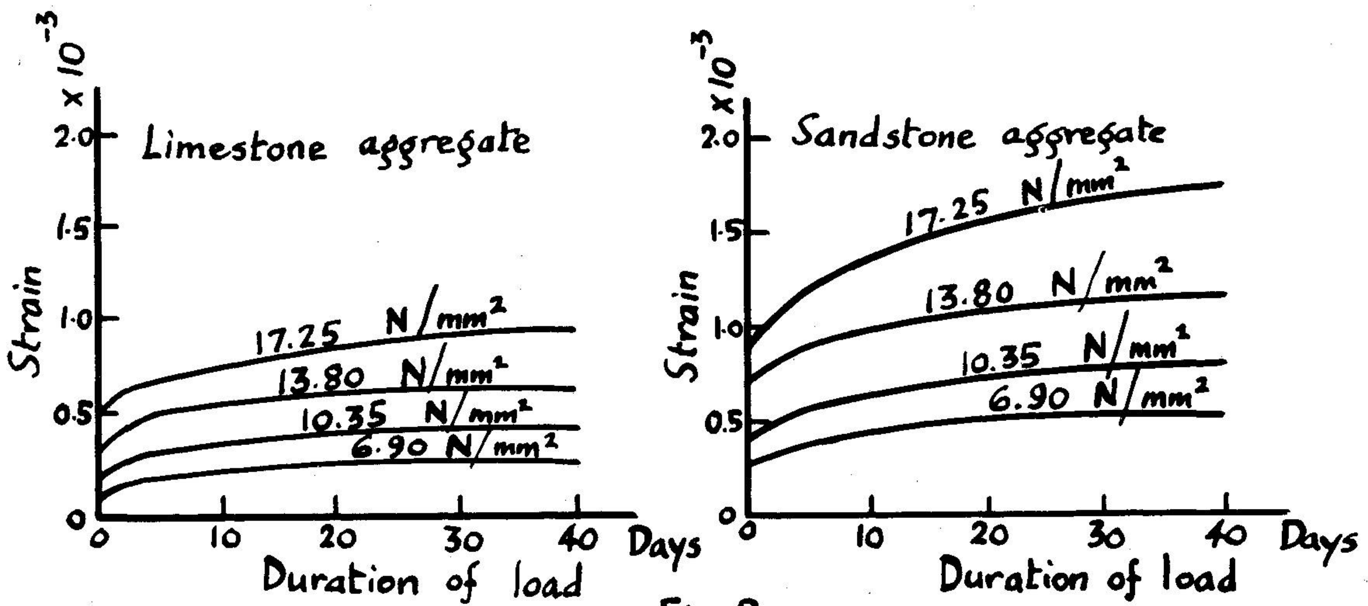

Fig. 2

d) In addition, six pretensioned concrete beams of which three contained limestone, and three sandstone, aggregates were tested for camber and ultimate flexural capacity. The beams were cast in long-line pairs so that initial prestress was identical for the members of each pair. Prestress was transferred at 7 days, and the camber was measured for 3 days before loading test. The cross-section of the beams was 127 x 178 mm; overall length 3 m. The prestressing force was applied by nine 5 mm indented wires, initially stressed to 1100 N/mm^2 whose resultant acted 60 mm from the bottom of the section. The effective span under center point loading was 2.44 m.

A summary of test results is given in Table IV and load deflection curves for the beams are plotted in Fig. 3. For beam pairs 2 and 3, 150 x 300 mm cylinder specimens of the concrete were subjected to compressive strain measurement to failure using Demec reading at 120° as for the creep specimens. The results are shown in Fig. 4.

Table IV

Beam Mark	1L	1S	2L	2S	3L	3S
Concrete Strength at 10 days, N/mm^2	29.0	31.6	29.7	44.2	25.6	40.0
Camber on release, mm	2.3	3.3	1.8	2.8	2.5	3.2
Camber 3 days after release mm	2.5	4.1	2.9	3.6	3.4	4.2
Ultimate center point load, kN	33.4	39.0	31.8	41.6	30.5	40.5
Ultimate moment at failure cross section, M_T, kNm	18.6	20.8	17.8	23.3	17.1	22.6
Calculated ultimate moment* M_u, kNm	18.5	18.9	18.5	21.6	17.1	20.4
Ratio M_T/M_u	1.01	1.10	0.96	1.08	1.00	1.11

*Based on Hognestad et al.[6]

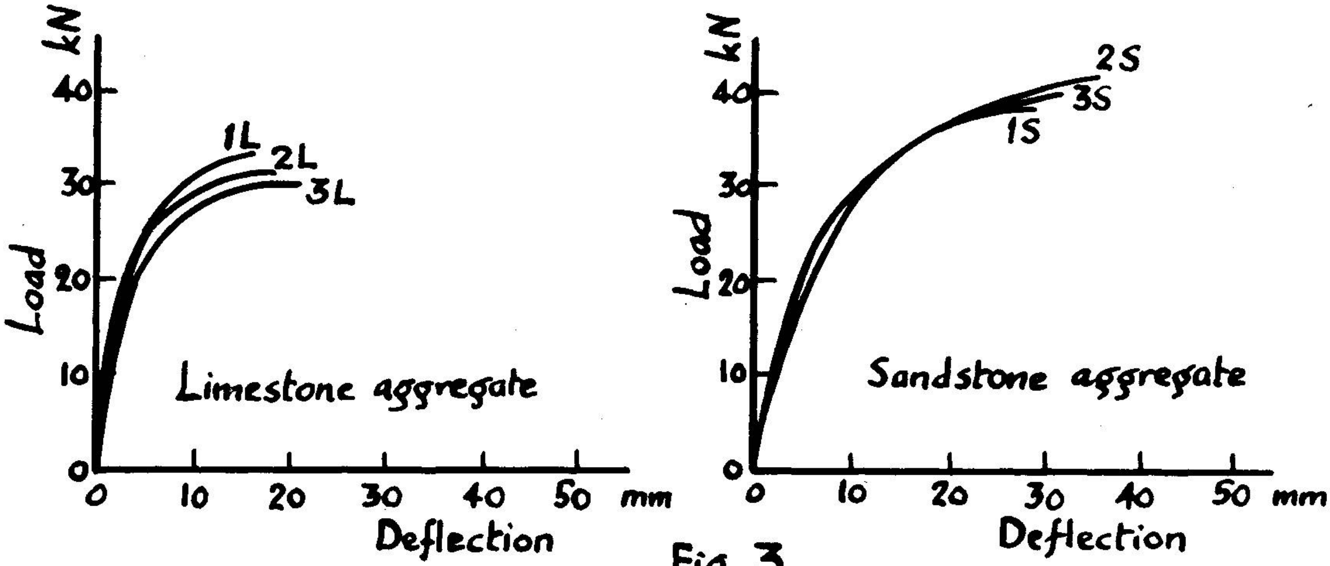

Fig. 3

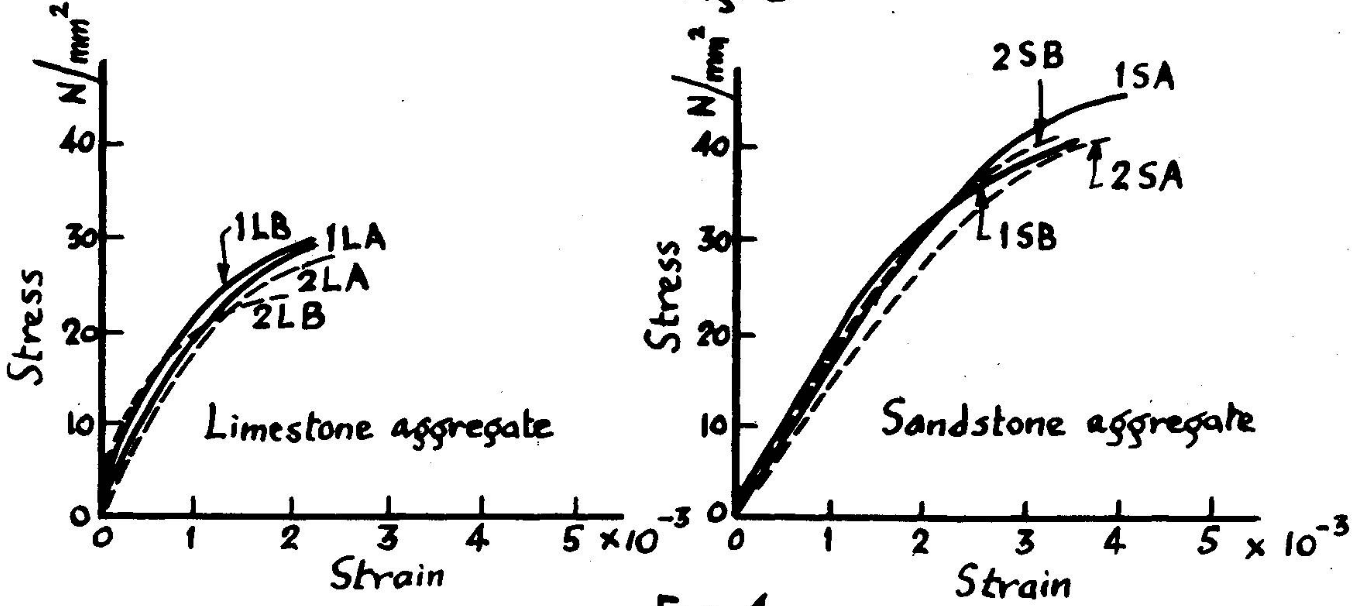

Fig. 4

e) Tests on slender reinforced concrete columns subjected to load eccentric about the major axis, which were performed by Tharasak,[7] included three pairs of specimens in which the effects of limestone and sandstone aggregates were compared. The results for these tests, given in Table V, indicate the reduction in flexural rigidity B_1 about the minor axis, corresponding to the lower effective modulus, for the columns made with sandstone aggregate concrete, although there is little difference in the calculated ultimate load P_u (ignoring the effects of slenderness) based on the concrete compressive strength. All the columns represented in the Table failed by lateral buckling at loads less than P_u and also less than the theoretical buckling load P_{c1}, about the minor axis, calculated from the values given.

Detailed analysis is presented in a report on the complete test series,[8] and it is only intended here to draw attention to the reduced failure loads of the sandstone aggregate columns of series 2 compared with their limestone companions. From this it follows that in the estimation of the strength of structures affected by slenderness, it is not safe to base the effective modulus value on the compressive strength, which was also the case for the camber deflections of the prestressed beams reported above.

Table V

Specimen details: overall length 2.08 m
Cross-section: overall depth 254 mm
" breadth 76 mm (Series 1)
" " 51 mm (Series 2)

Specimen Mark	(Series 1) 11	12	(Series 2) 21	22	23	24
Aggregate type	L	S	L	S	L	S
Concrete Strength (N/mm^2)	30.3	30.4	30.7	28.8	26.2	31.2
Load eccentricity (mm)	203	203	203	203	254	254
Flexural rigidity B_1 ($kNmm^2$)	647	612	169	132	218	172
Calc. buckling load P_{c1} (kN)	592	535	154	121	204	157
Calc. ult. load P_u (kN)	208	209	163	159	130	134
Test load P_t (kN)	182	187	109	91	88	67

Discussion

The following table gives a comparison of the effective moduli for short and long term loading from tests (a) and (c) with the values proposed by some design codes of practice. The values E_i are based on the instantaneous deformation under the stress level of 13.8 N/mm^2, and E_t on the creep (i.e., total deformation minus shrinkage) at 28 days after commencement of test. The draft British Standard Code[9] and the new ACI proposals[10,11] give good agreement with the results for limestone aggregate concrete, but for other aggregates, particularly sandstone, the test results give substantially lower effective moduli values, whilst the calculated values are marginally increased or unchanged. Both codes refer to the possibility that certain types of aggregates may give deformations greater than predicted by the formulae without giving any specific guidance. It is hoped that this paper will be regarded as providing some data, but further evidence is required to enable a more comprehensive equation to be developed.

Test	Aggregate	Test Results		B.S. Code 1959		ACI 318-63 Proposed Revision 1970		CP 115 1959
		E_i kN/mm^2	E_t kN/mm^2	E_c kN/mm^2	E_{ct} kN/mm^2	E_c kN/mm^2	E_{ct} kN/mm^2	E_c kN/mm^2
Ser. I	Limestone	29.3	11.9	29.8	7.9	29.8	11.9	36.0
	Sandstone	16.4	7.0	31.5	8.3	30.0	12.0	38.2
	Andesite	23.4	9.3	30.8	8.1	31.6	12.6	37.4
	Gravel	22.6	9.6	29.5	7.8	28.8	11.5	35.2
Ser.II	Limestone	36.0	18.2	31.8	9.1	32.9	13.2	38.6
	Sandstone	19.4	11.5	33.0	11.0	31.5	12.6	40.6

In the tests of prestressed concrete beams, the relative cambers and deflections are as expected, and the high ultimate load of the sandstone aggregate beam is caused not only by the concrete strength but more significantly by its high ultimate strain capacity. This has important implications in the study of moment-rotation capacity of continuous structures and in stability problems as in the test of reinforced concrete slender columns.

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SUMMARY

The effect of variation in the physical properties of coarse aggregate between commonly used types as exemplified by limestone, sandstone and others, on the compressive strength and deformation of concrete under sustained loading, was studied (a) by keeping all other quantities constant and (b) by adjustment of the water-cement ratio to give constant workability. The results are of significance in the design of prestressed concrete and of continuous beams and slender compression members in reinforced concrete.

RESUME

On a étudié l'influence des propriétés physiques des agrégats de grandes dimensions par rapport aux agrégats couramment utilisés (p. ex. le calcaire ou le grès) sur la résistance à la compression et sur les déformations du béton soumis à une charge constante, (a) sans varier les autres proportions, (b) en adaptant le rapport eau-ciment pour obtenir la consistence habituelle. Ces résultats sont importants pour le calcul du béton précontraint, des poutres continues et des colonnes élancées comprimées en béton armé.

ZUSAMMENFASSUNG

Der Einfluss der Veränderung der physikalischen Eigenschaften der Zuschlagstoffe zwischen gewöhnlichen Sorten (zum Beispiel Kalkstein und Sandstein) auf die Druckfestigkeit und die Formänderung des Betons unter ständiger Belastung wurde untersucht: (a) durch Konstanthalten aller anderen Mengenverhältnisse und (b) durch Berichtigung des Wasserzementfaktors. Die Ergebnisse sind wichtig für die Berechnung des Vorspannbetons und der durchlaufenden Balken sowie der schlanken Säulen aus Stahlbeton.