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Waste Materials in Construction: Putting Theory into Practice

STRUCTURAL PERFORMANCE OF REINFORCED CONCRETE MADE WITH SINTERED ASH AGGREGATE

P. J. WAINWRIGHT[1] P. ROBERY[2]

1. SENIOR LECTURER, DEPARTMENT OF CIVIL ENGINEERING, UNIVERSITY OF LEEDS, ENGLAND.

2. DIRECTOR, G. MAUNSELL & PARTNERS, CONSULTING ENGINEERS, BIRMINGHAM, ENGLAND

Summary

Previously published work has described a process in which the bottom ash from MSW incinerators has been treated to produce a coarse aggregate suitable for use in concrete. Data has been given on the production parameters, the physical properties of the aggregate and their influence on some of the material properties of the concrete, the data presented here is an extension to that work. The structural performance of concretes made from aggregates derived from MSW incinerator residues is compared with that of concretes made from a natural aggregate and from a commercially available lightweight aggregate (Lytag). Tests were performed to measure strength, deformation, bond, load deflection and cracking characteristics of reinforced concrete beams. The results showed that overall the performance of the incinerator aggregate was similar to that of Lytag and compared favourably with that of the natural aggregate. The structural behaviour of all beams was predictable using the design standard that was applicable at the time the tests were carried out.

Introduction

Previously published work by the authors (1- 7) described a process where by an artificial aggregate was produced from the ashes derived from municipal solid waste (MSW) incinerators. The ashes were treated to remove all ferrous and non ferrous metals and were further crushed, blended with clay , pelletised and then fired in a kiln. The properties of the aggregates made with ashes from two different sources were compared with those of a natural gravel aggregate and a number of tests carried out to measure the performance of the material in concrete. Tests were performed over a period of over 4 years measuring such properties as :- compressive and tensile strength development, elastic modulus, shrinkage and creep. A study was also undertaken into the durability of the concretes made with the material looking in particular at the corrosion rates of reinforcement and the susceptibility to attack by the alkali silica reaction.

As expected the results showed that the material did not perform as well as the natural aggregate but never the less , considering the nature of the material, its performance was considered satisfactory and more importantly there were no indications of any long term detrimental reactions taking place.

In the majority of the tests undertaken in the work referred to above comparisons have been made between the ash aggregate and a natural gravel aggregate. However by its nature the ash aggregate is more like a lightweight aggregate than a natural aggregate and it was therefore decided to carry out a study comparing its properties with that of a commercially available lightweight material. Emphasis in this study was placed on the structural performance in reinforced concrete beams as well as looking at the more fundamental properties of small scale concrete specimens.

Experimental work

Materials and their properties

The aggregate used in this study was that manufactured from the ashes of the Dutch incinerator in Rotterdam as described previously (7). Comparisons were made between this material and :-

a). A 10 mm. single size lightweight aggregate made from sintered fly ash and sold under the trade name of Lytag.

b). A 10mm single size, irregular, quartzitic gravel aggregate.

The relevant properties of the aggregates are shown in Table 1

Mix Proportions

All concrete mixes were designed to have nominally the same strength at 28 days and similar aggregate volume proportions. The sand / cement ratio was kept constant at 2 / 1 (by volume) and the coarse aggregate volume concentration was 0.48 for the gravel aggregate concrete and 0.4 for the other two.

The concrete made from the natural aggregate had a water / cement ratio of 0.59 and a nominal cement content of 315 kg / m^3 ; whereas for the concretes made from the ash and Lytag aggregates the figures were 0.48 and 385 kg / m^3 respectively.

Both the lightweight aggregates were pre-soaked for 30 minutes before casting and all concretes were made to nominally the same workability of 100mm slump. Following casting all specimens were kept under water at 20^{0}C until testing.

Tests Performed

The following tests were performed at the appropriate ages in accordance with the relevant British Standard (8) :-

- Compressive strength on 100mm. cubes
- Flexural strength, static and dynamic modulus of elasticity on 100 x 100 x 500mm. prisms.

The following non standard tests were also performed to help assess structural performance :-

- Bond Strength

  Bond strength was determined using two methods (9) namely the Pull out test to measure anchorage bond and the Transfer test to measure adhesion bond.

- Reinforced concrete beam tests.

The load deflection, ultimate load carrying capacity and cracking characteristics were assessed on a number of reinforced concrete beams details of which are given in Table 2. Three different reinforcement ratios were chosen to cover the range from under to over reinforced. Beams were tested over a span of 2.4m using a two point loading system. All structural design calculations on the beams were carried out in accordance with the Code of Practice that was appropriate at the time the tests were being conducted.

The beams were loaded to their design load then cycled 5 times from 5kN to the design load before being loaded to failure. Measurements were taken on mid span deflection, strain distribution and crack width.

Results

Compressive / Flexural Strength

Results for compressive strength are shown in brief in Table 2 and in some more detail in Fig 1. All mixes show similar strength development characteristics and were relatively close to their design strength of 40.0 N/mm^2 at 28 days. Comparing the Lytag concretes with the Ash concretes (made with the same w/c and cement content) it can be seen that the former was approximately 30 % stronger at 28 days which is probably indicative of a better quality material.

Flexural strength results are summarised in Table 2 and it is interesting to note that, as with compressive strength the results for Lytag and gravel are similar yet unlike compressive strength the ash concrete achieves a higher strength albeit only marginally (approx. 7%).

Elastic Modulus

The relationship between elastic modulus (dynamic) and strength is shown in Fig. 2; the ash and Lytag concretes show a similar relationship, but as expected, for a given compressive strength the natural gravel concrete has a modulus which is approximately 1.6 times larger than the other two.

Bond Characteristics

Results from a typical pull out test showing bar slip against average bond stress are shown in Fig. 3. Somewhat surprisingly the ash concrete shows a significantly lower slip for a given bond stress than the other two. The stress required to produce a given slip is believed to increase with an increase in both the mortar strength and the elastic modulus of the concrete. Direct comparisons between the natural aggregate concretes and the other two are therefore difficult because, on the one hand the mortar strength of the former is likely to be lower because of the higher water / cement ratio yet, on the other hand, the modulus of elasticity is higher. Comparisons between the two lightweight concretes should though be valid but no reason can be given at present to explain the significantly lower slip values of the ash aggregate concrete

The results of average bar stress against average bond stress as measured by the bond transfer test are shown in Fig. 4 and show a more logical trend than the pull out test. For a given bar stress the bond stress for the gravel concrete is approximately 40% lower than for the two lightweight concretes, this is difference is probably due to the weaker mortar strength of the former as reported earlier.

Structural Behaviour

Some of the results of tests carried out to study the structural behaviour of reinforced concrete beams when loaded in the manner described previously are summarised in Table 3.

It is to be expected that the lightweight aggregate concrete beams will deflect more at ultimate design load than those made with natural aggregate concrete due to the lower modulus of elasticity. The results however show no obvious trend and in fact in only one of the series (series 1 over reinforced) does the natural aggregate concrete show a lower deflection than either of the two lightweight concretes. Load deflection curves for series 3 (reinforced with 2 Y -16 bars) are shown in Fig. 5 , in this particular set of tests the ash concrete beams show the highest deflection (which was to be expected) but the Lytag beams deflected the least. The differences though are only small, for example at the design load of approximately 30.0 kN the differences between all three tests is only about 12 % and from Table 3 the maximum difference at the design moment for all tests was no more than 15%.

The structural performance of the beams was also assessed using the UK design code which was applicable at the time, the characteristic curve for the flexural strength of a member was obtained from a graph of :-

$$\frac{Mu}{fcu\ bd^2} \quad \text{against} \quad \frac{As}{bd} \cdot \frac{fy}{fcu}$$

The relationship between these two terms is shown in Fig. 6 together with the results of all the twelve beams tested. It can be seen that the results for all beams lie outside the ultimate limit state envelope used by the code and that they all follow a similar trend regardless of the type of concrete used.

The figures for both average crack width and spacing at the ultimate design moment are given in Table 3; both can be seen to be greater for the lightweight concretes than for the natural aggregate which is what was expected. However more importantly none of the values recorded were outside the limits recommended by the code and in general the values for the ash concrete are lower than those of the Lytag concrete.

The strain distribution about the centre of each beam was measured for each increment of load and in every case the stains were seen to be distributed approximately linearly above the neutral axis . In addition the position of the neutral axis was in general lower for the lightweight concrete beams due to their lower elastic modulus.

Conclusions

The following conclusions can be drawn from the work reported here.

- The deflections of reinforced concrete beams at the ultimate design moment made with the ash aggregate compare favourably with those of beams made from the natural aggregates and were less than those beams made with Lytag concrete.
- The average crack width and spacing was similar for lightweight aggregate concretes; they were both higher than the natural aggregate concrete but still within the limits of the structural code.
- The shape of the stress strain distribution curve was similar for all beams but the depth of the neutral axis in the lightweight concrete beams was lower.
- The anchorage bond strength was higher for the natural aggregate concrete than for the lightweight concretes of similar mortar strengths. The cohesion bond was however lower when comparisons were made on the basis of equal concrete compressive strength.
- Overall the structural performance of the incinerator ash concrete was similar to that of the Lytag concrete and compared favourably with the natural aggregate concrete.

References

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Table 1 Aggregate Properties

Source	Bulk Density (kg/m^3)		Relative Density	Water Absorption %
	Loose	Rodded		
10mm gravel	1525	1626	2.61	0.6
Ash	1059	1121	2.29	10.11
Lytag	896	962	1.75	12.20

Table 2 Reinforced concrete beam details

Beam No.	Agg. Type	Comp. Str. N/mm^2		Flex. Str. N/mm^2		Elast. Mod. KN/mm^2		b x d mm.	Reinf. Type	Steel ratio
		28d.	6m.	28d.	6m.	28d.	6m.			
H1	Ash	37.5		4.6		20.2		120x172	3-Y16	2.92
H2			44.6		4.68		22.4		3-Y16	2.92
H3		37.5		4.6		20.2			2-Y16	1.95
H4		37.5		4.6		20.2			2-Y12	1.08
G1	Gravel	45.0		4.3		32.7		120x164	3-Y16	3.03
G2			52.3		4.44		35.8		3-Y16	3.03
G3		45.0		4.3		32.7			2-Y16	2.09
G4		45.0		4.3		32.7			2-Y12	1.12
L1	Lytag	50.0		4.35		23.3		120x172	3-Y16	2.92
L2			57.8		5.18		25.5		3-Y16	2.92
L3		50.0		4.35		23.3			2-Y16	1.95
L4		50.0		4.35		23.3			2-Y12	1.08

Note :- Overall dimensions of all beams 2600 x 120 x 200mm.

Table 3 Summary of reinforced concrete beam results

Beam No.	Cracking moment kNm. Mcr	Ult. des. moment kNm. Mud	Ult. des. failure moment kNm. Mu	Exp. ult. failure moment kNm. Mue	Deflection at Mud mm.	Av. crack width at Mud mm. x 10^{-2}	Av. crack spacing at Mud mm.
H1	4.59	24.9	35.7	35.5	7.10	9	78
H2	5.99	26.2	36.8	36.8	6.45	4	88
H3	3.86	19.3	25.3	24.4	7.05	6	74
H4	3.78	12.2	15.2	17.4	5.6	8	78
G1	4.68	25.0	34.9	38.1	7.00	6	75
G2	5.29	26.5	35.7	42.0	7.00	6	70
G3	3.85	19.0	24.5	27.6	6.95	6	70
G4	3.49	12.0	14.6	18.8	5.65	5	78
L1	3.99	27.6	37.4	37.1	7.8	10	88
L2	5.82	28.4	38.1	39.9	7.45	6	84
L3	3.74	20.5	26.1	28.9	6.3	5	70
L4	3.48	12.6	15.4	18.7	5.1	7	78

Fig. 1 Compressive strength development

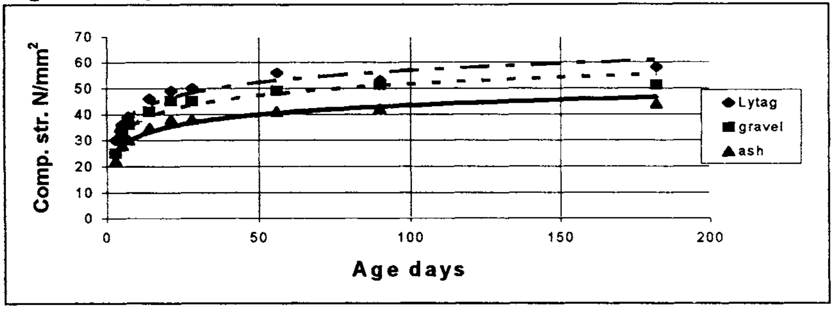

Fig. 2 Relationship between compressive strength and elastic modulus

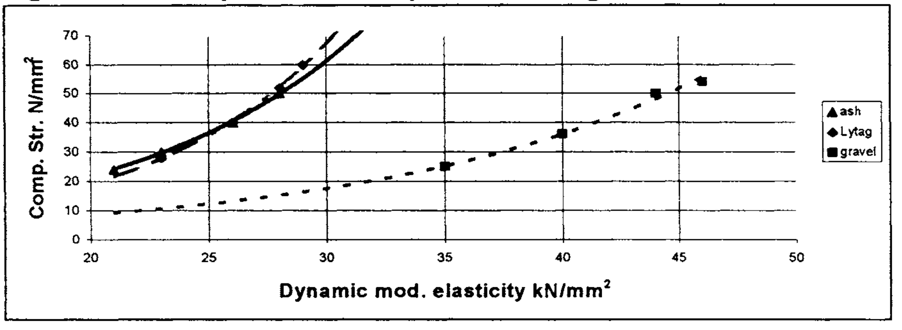

Fig. 3 Relationship between average bond stress and bar slip

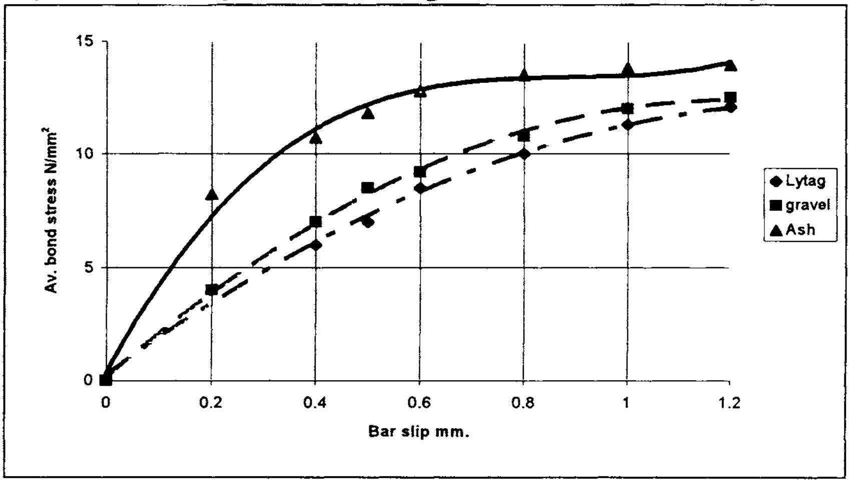

Fig. 4 Average bond stress against bar stress

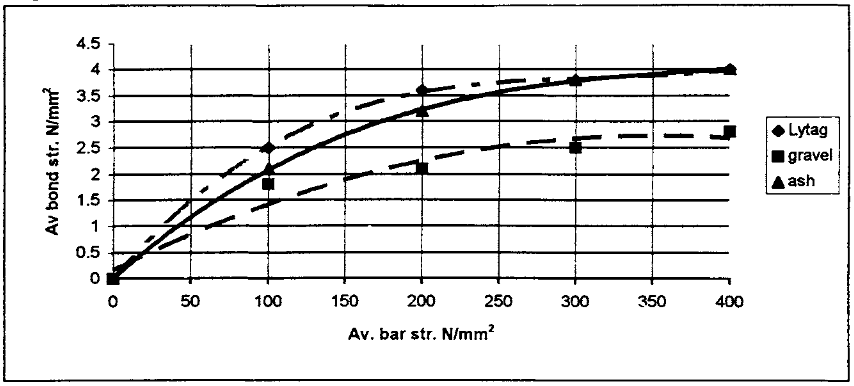

Fig. 5 Load deflection relationship for beams with 2 Y- 16 reinforcement

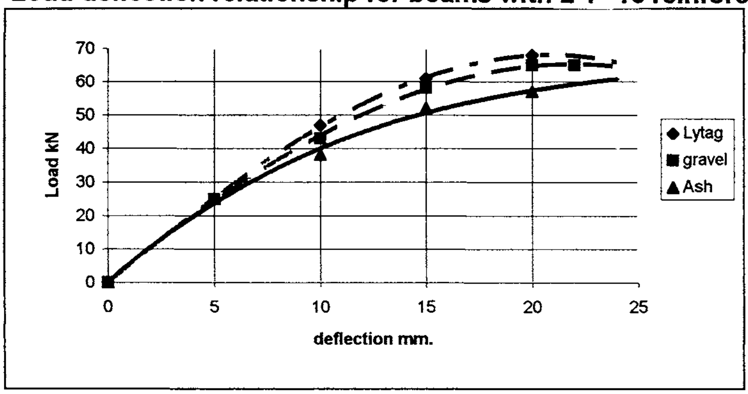

Fig. 6 Characteristic curve for flexural strength