Shear strength of lightweight aggregate concrete

by J L Clarke, Cement and Concrete Association

Lightweight aggregate concrete has been available for a number of years but apart from block masonry, has not been widely used in structural applications. Some notable structures have been built however, such as grandstands, using prestressed lightweight concrete having a characteristic cube strength up to 60N/mm². Lightweight aggregate concrete has been used on a very small scale for bridges in the UK but in America and on the Continent, it has been used for a number of structures[1], showing overall savings in total cost of between 10 and 20 per cent of the equivalent normal weight structure.

Most of the lightweight aggregates suitable for concrete are factory made and include sintered pulverised fuel ash, pelletised slag and expanded clay, shale and slate[2]. Those suitable for structural use, ie above 25N/mm² at 28 days, will have densities between 1400kg/m³ and 2000kg/m³. It is possible to achieve strengths in excess of 50N/mm² but this is usually done by using lightweight coarse aggregate combined with a natural sand. This obviously limits the weight savings but, typically, a sintered pulverised fuel ash aggregate with a natural sand will give a density in the region of 1900kg/m³, a reduction of over 20 per cent when compared with normal concrete.

The use of lightweight aggregate concrete is included in both BS 8110[3], the code of practice for structural concrete and the bridge code, BS 5400[4], but its use may be somewhat restricted by the reduced permissible stresses in shear and torsion, which are taken as being 80 per cent of those of dense concrete. The effects will be partly offset for lightly loaded structures by the reduced self weight stresses.

While there is some published information on the structural behaviour of lightweight aggregate concrete, much of the work in this country has been sponsored by the aggregate manufacturers. Tests are being carried out at the Cement and Concrete Association to obtain independent data, in the light of which the other work and the requirements of the codes of practice may be evaluated. The tests are looking at the behaviour of beams, with and without stirrups, in shear but in addition limited tests on the long-term deflections of beams are also being carried out.

The investigation is restricted to Lytag and Pellite, the only two lightweight aggregates currently available in the UK which can be used to produce a structural grade of concrete. Lytag is sintered pulverised fuel ash manufactured by Pozzolanic Lytag and Pellite is pelletised blastfurnace slag manufactured by Tarmac Pellite Ltd.

Research on shear

Extensive work was carried out in the United States of America in the 1950s and 1960s on the shear behaviour of lightweight aggregate beams without shear reinforcement by researchers such as Hanson[5]. The effects of the span to effective depth ratio and the area of the main steel on the shear capacity were considered by Ivey and Buth[6]. Their work, along with that of Hognestad, Elstner and Hanson[7], on the shear behaviour of lightweight aggregate slabs forms the basis of the recommendations in the American Concrete Institute building code[8].

The results obtained by Hanson and by Ivey and Buth were compared with the predicted values from BS 8110. The theoretical strengths were obtained with the partial safety factor of 1.25 removed, using the measured concrete strengths. (Cylinder strengths have been taken as equal to 0.8 of the equivalent cube strengths.) In line with the code requirements, no increase in shear capacity was taken for concretes in excess of 40N/mm². It was found that the BS 8110 equation was generally conservative; the mean value for the ratio of actual to predicted strength for the 47 results was 1.5 with only 3 being below 1.0. Some of the high ratios were obtained from beams with a shear span : depth ratio of 2.0; BS 8110 only gives an increase in shear capacity for shear span : depth ratios of less than 2.

In the United Kingdom Hamadi and Regan[9], carried out shear tests on Tee beams with shear reinforcement. Ten beams were tested in all, five using a normal dense aggregate and five using a lightweight (Leca, expanded clay) aggregate. All were tested with the same shear span to depth ratio but the results give a useful indication of the relative behaviour of stirrups in lightweight and dense aggregate concrete : the codes all assume that the shear carried by the stirrups is not influenced by the aggregate type.

Berge[10] tested rectangular lightweight beams with and without stirrups in shear. He considered a range of densities and strengths from about 1150kg/m³ and 10N/mm² up to about 1900kg/m³ and 50N/mm². Each set of three beams at a given density and strength consisted of one without stirrups and two with stirrups. In all seven beams had strengths

	Lytag	Pellite
Coarse : fine	0.53 : 0.47	0.6 : 0.4
Aggregate : cement ratio	4.5	3.8
Effective water : cement ratio	0.7	0.47

Table 1

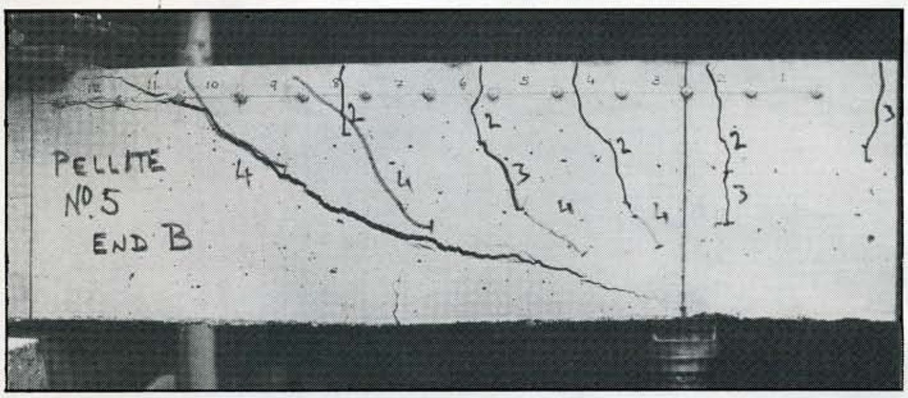

Figure 1: Failure of beam without links

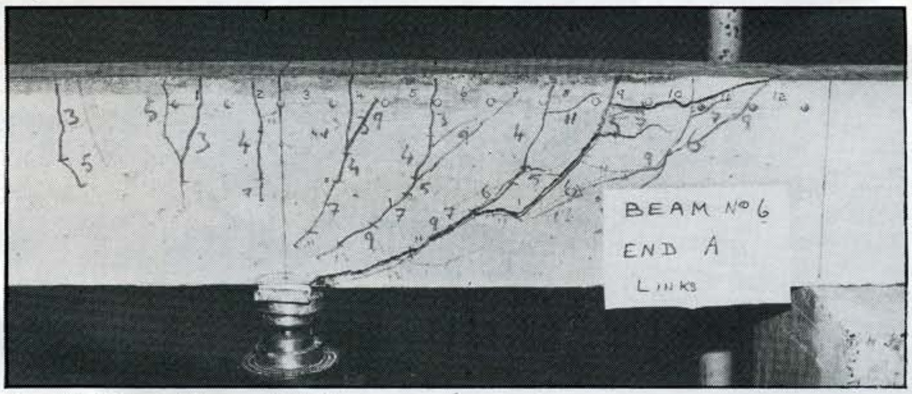

Figure 2: Failure of beam with links

above 25N/mm² and therefore may be compared with the equation in BS 8110. His results and those from Hamadi and Regan are considered later.

Shear tests

Test specimens

As far as possible the series of tests on the Lytag and the Pellite beams were the same.

All the beams were 100mm wide by 200mm deep by 3m long. The beams had links at one end only with the same amount of main tension reinforcement running throughout. Thus it was possible to obtain a direct measure of the capacity of the links as well as of the concrete section alone. High yield steel was used for the main reinforcement and mild steel for the stirrups.

Concrete

The concrete mixes, using lightweight coarse aggregate and Thames Valley natural fines, were as given in Table 1.

This gave a cube strength at the time of testing of about 55N/mm² for the Lytag beams and a density of about 1900kg/m³. The figures for the Pellite beams were about 45N/mm² and 2000kg/m³ respectively.

Because lightweight aggregates are very absorbent some of the water was added to the aggregate and sand and allowed to stand for about 15 minutes before mixing. The cement was then added along with sufficient additional water to give a suitable workability.

The beams were demoulded at 24 hours, stored under polythene for a further 6 days and then in the laboratory at 20° before being tested at approximately 28 days.

Test arrangement

The beams were tested with a shear span : effective depth of 3.0. In all cases the end of the beam without links was tested first followed by the end with links. The shear load was increased in increments of 5kN. Cracks were marked in at each load stage and the strains at the level of the steel were measured using a continuous line of demec points on a gauge length of 50mm.

Test results

There were no obvious differences between the beams made with Lytag and those made with Pellite and hence they have been considered together.

For beams without links, the crack development was always the same. Figure 1 shows a typical pattern. Flexural cracks formed at first, those at mid-span tending to turn in towards the loading point. Failure occurred with a major shear crack running from the load to the support, often unrelated to any pre-existing crack.

For beams with links the initial load stages were similar to those without, with flexural cracks developing and curving in towards the support, forming shear cracks. The pattern of the inclined cracks, see Figure 2, was dictated by the links, which were spaced at 125mm. In some beams failure was similar to that on the beams without links, with a major shear crack developing running from the load to the support, with the links crossing it yielding and rupturing. In other beams, the same crack pattern developed but failure was in the compression zone over the load.

Discussion of results

The maximum loads of the beams have been compared with the predicted shear capacities from the BS 8110 equation. As specified no increase has been allowed for cube strengths in excess of 40N/mm². The stirrup capacities have been calculated on the basis of the specified characteristic strengths of the steel.

Without links the ratio of actual to predicted strength ranges from 1.29 up to 2.30 with a mean of 1.64. For the beams with links the ratio ranges from 1.44 up to 2.10 with a mean of 1.75. The values for the permissible shear stresses in BS 8110 were obtained by taking mean values of test results and then applying a partial safety factor of 1.25 to give a design value. On the basis of the 15 tests on beams without links, the mean value of 1.64 would suggest that the factor of 0.8 applied for lightweight aggregate could be removed. This would give a mean value for the ratio of 1.31. The lowest strength achieved would still be slightly above the design value. However, some other published data do not support these conclusions fully, but suggest that a reduction factor of 0.9 could replace the 0.8 in the code.

For beams with links the actual failure loads have been compared with the design values obtained from BS 8110, without the 0.8 reduction factor for lightweight. The resulting ratios of actual to design strength are plotted in Figure 3 along with the results from Berg and from Hamadi and Regan for beams with a concrete strength of more than 25N/mm². It may be seen that all beams carried at least 20 per cent more than the design shear capacity indicating that the 0.8 reduction factor is not justified for beams with links.

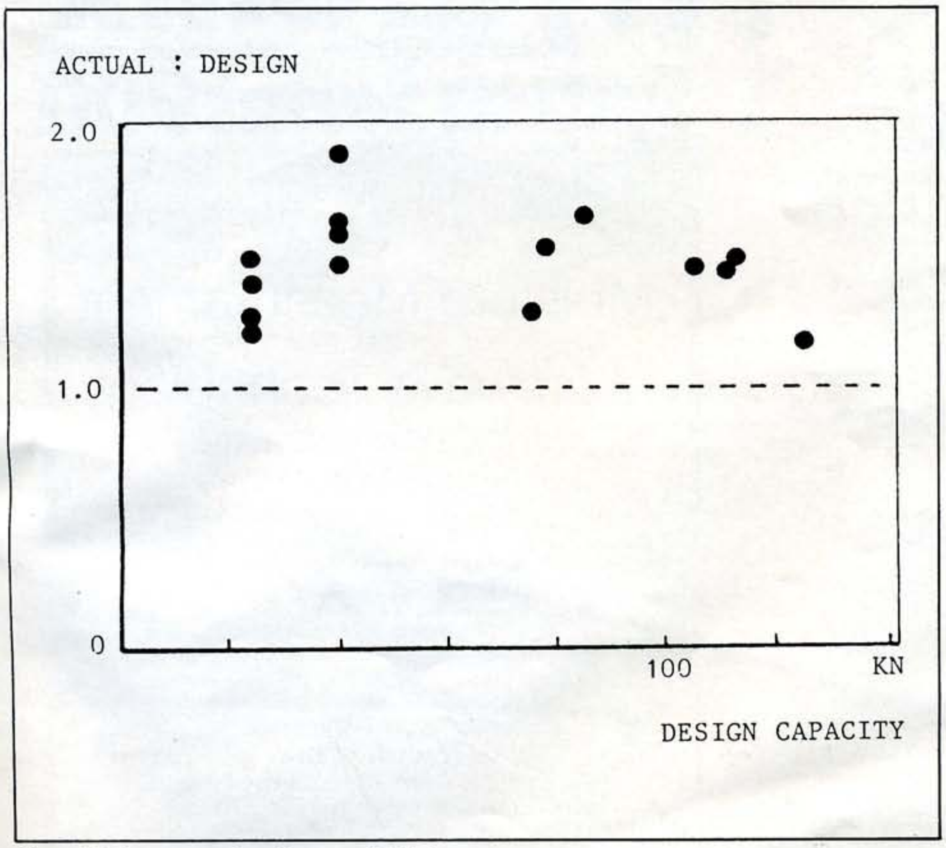

Figure 3: Shear strengths of beams with links

Conclusions

The limited tests carried out have suggested that the code of practice requirements for shear are unnecessarily conservative. For beams with links there is no need to introduce a reduction factor. For those without the factor need only be 0.9 instead of the 0.8 in BS 8110.

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