Deformation Behaviour of Reinforced Polystyrene Concrete Beam

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SUMMARY

An experimental investigation was conducted to compare the flexural behaviour of reinforced concrete beams with normal-weight and polystyrene-aggregate concrete mixes with the aim of extending the application of lightweight polystyrene concrete to structural members. Dimensions and reinforcement details for both the normal-weight and polystyrene concrete beams are identical, and the 28-day compressive strengths of both types of concrete are similar. Analysis of the test results indicates that AS3600 rectangular stress block method of analysis provides accurate and conservative prediction of the ultimate bending capacity for both the normal-weight and polystyrene concrete beams. The Simplified Method of calculating beam deflections as set out in AS3600 is under-estimated the short-term deflections of the polystyrene aggregate concrete beam and Gergely-Lutz equation may be used to predict the maximum crack width for the reinforced concrete beams with both normal weight and polystyrene aggregate concrete mixtures.

INTRODUCTION

Expanded polystyrene is an extremely lightweight material and extensive investigation into the properties of polystyrene-aggregate concrete (PAC) has been conducted at the University of Technology, Sydney for the last five years (1-3). So far, the primary use of PAC has been the manufacture of non-structural components of concrete buildings including perimeter insulation, roof insulation and masonry insulation (4, 5).

The structural use of PAC is of much interest to engineers since it is envisaged that structural members made with PAC would have certain advantages over those made with normal weight concrete. These are namely: (a) the lighter weight precast polystyrene aggregate concrete members would be easier to handle; (b) the formwork would need to withstand a lower pressure; (c) the size of the foundation can be reduced; (d) the lower thermal conductivity of PAC would improve the fire rating of the building; and (e) the better energy-absorbing capacity of PAC would be beneficial in structures which are likely to be subject to dynamic or impact loading such as buildings in earthquake zones and buildings which store explosives.

Previous investigation had shown that with a 10% replacement of coarse aggregate in normal weight concrete by expanded polystyrene beads and with the use of superplasticizer,
polystyrene-aggregate concrete having the 28-day cylinder compressive strength of 50 MPa can be produced (6). However, the structural use of the polystyrene aggregate concrete has been prevented by the lack of knowledge on the structural behaviour of polystyrene-aggregate concrete members. This paper reports the results of an experimental investigation into the flexural behaviour of reinforced concrete beams made with both normal-weight and polystyrene-aggregate concrete mixtures.

**EXPERIMENTAL DETAILS**

**Materials and Mixture Proportions**

Two reinforced concrete beams having, identical dimensions and reinforcement details, were made using normal weight concrete and polystyrene aggregate concrete. The target 28-day cylinder compressive strength for both types of concrete mixes was 32 MPa. In order to achieve an economical concrete mixture, low-calcium fly ash from NSW was incorporated in the polystyrene aggregate concrete mixture.

Table 1 summarises the mixture compositions for both types of concrete. Polystyrene aggregate concrete mixture had the water to cement ratio of 0.44 compared to 0.62 for the normal weight concrete. This drop in water to cement ratio was necessary to achieve the same strength in the PAC compared to the normal weight concrete. The binder (cement plus fly ash) content in the PAC was 555 kg/m³ compared to 380 kg/m³ in the normal weight concrete.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Normal Weight Concrete (kg/m³)</th>
<th>Polystyrene Aggregate Concrete (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>380</td>
<td>445</td>
</tr>
<tr>
<td>Water</td>
<td>235</td>
<td>195</td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td>915</td>
<td>670</td>
</tr>
<tr>
<td>Coarse Aggregate</td>
<td>840</td>
<td>750</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>-</td>
<td>110</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>-</td>
<td>3.1</td>
</tr>
<tr>
<td>Polystyrene bead</td>
<td>-</td>
<td>5.45</td>
</tr>
<tr>
<td>W/C Ratio</td>
<td>0.62</td>
<td>0.44</td>
</tr>
</tbody>
</table>

The expanded polystyrene aggregate, in the form of spherical-shaped beads, was commercially available with suitable chemical coating which is necessary to achieve a uniform dispersion of the beads in the fresh concrete mixture and to avoid segregation during mixing and handling of concrete. The polystyrene beads had the mean diameter of 2.6 mm and the bulk density of 55 kg/m³. Since the workability of concrete is reduced by the presence of lightweight polystyrene beads, superplasticizer was used to improve the workability of the polystyrene aggregate concrete mixture.
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Reinforced Concrete Beam Details and Instrumentation

Fig. 1 shows the details of the reinforced concrete beams. Two 16 mm diameter high-tensile steel (yield stress of 450 MPa) bars were used as main tension reinforcement and 10 mm bars mild-steel bars were used at the ends of the beams in the compression zone. The reinforcement content was chosen to obtain under-reinforced concrete beams.
Fig. 2 shows the loading arrangement for the reinforced concrete beams. The beams were tested to failure under slowly increasing flexural loading and LVDTs (linear voltage displacement transducers) were used to monitor the deflection of the beams at mid-point during the test at each load increment. Data logger was used to record the deflections automatically during the test.

In order to monitor the bond slippage of the tensile bars in the polystyrene reinforced concrete beams, the concrete cover at both ends of the beam was chipped away to expose the bottom bars and LVDT set against the exposed bar ends. Demec points were attached to the concrete surface in the central region of the beams and electrical strain gauges were placed to check the strains measured by the demountable mechanical strain gauge. This arrangement, shown in Fig. 3, enabled to obtain the strain distribution across the cross-section at the mid-point of the beams.

Measurements of crack widths were made using a hand-held microscope capable of reading to an accuracy of 200 microns.

![Demec Points and Electrical Strain Gauges](image)

**Fig. 3** Demec points and strain gauges arrangement in the RC beams

<table>
<thead>
<tr>
<th>Properties</th>
<th>Normal weight concrete</th>
<th>Polystyrene aggregate concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump (mm)</td>
<td>85</td>
<td>140</td>
</tr>
<tr>
<td>Compacting factor</td>
<td>0.94</td>
<td>0.98</td>
</tr>
<tr>
<td>Vebe time (sec)</td>
<td>4.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Unit weight (kg/m³)</td>
<td>2405</td>
<td>2160</td>
</tr>
<tr>
<td>28-day Cylinder strength (MPa)</td>
<td>34.6</td>
<td>31.1</td>
</tr>
<tr>
<td>28-day Static modulus of elasticity (GPa)</td>
<td>30.1</td>
<td>26.6</td>
</tr>
</tbody>
</table>

**Table 2: Fresh and Hardened Properties of Concrete Mixtures**

**TEST RESULTS AND DISCUSSION**
Properties of Polystyrene Aggregate Concrete

Experience with polystyrene aggregate concrete (PAC) indicated that care must be exercised while mixing, pouring and compacting of fresh concrete to minimise segregation of the concrete mixture. It was noticed that fairly a uniform concrete may be achieved by limiting the amount of vibration to a period when polystyrene beads just start to accumulate at the top of the concrete member. But in order to achieve a good compaction at the same time, it was found necessary to add superplasticizer to the concrete mix to improve its workability. The addition of polystyrene beads reduced the workability of the concrete probably due to the water absorption by the patented coating to the polystyrene aggregate particles.

Table 2 summarises the workability and the properties of the normal weight and polystyrene aggregate concrete mixtures. The unit weight of polystyrene aggregate concrete was 2160 kg/m³ compared to 2405 kg/m³ for the normal weight concrete. Therefore, PAC is about 10% lighter than the normal weight concrete.

The workability of PAC is better than that for the normal weight concrete due to the use of superplasticizer. The 28-day compressive strength and static modulus of PAC were 31.1 MPa and 26.6 GPa respectively compared to 34.6 MPa and 30.1 GPa for the normal weight concrete.

Table 3: Predicted and experimental ultimate moment for RC beams

<table>
<thead>
<tr>
<th>Test Beam</th>
<th>Ultimate Moment (kN.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
</tr>
<tr>
<td>Normal weight concrete</td>
<td>52.5</td>
</tr>
<tr>
<td>Polystyrene aggregate concrete</td>
<td>51.0</td>
</tr>
</tbody>
</table>

Ultimate Flexural Strength of Reinforced Concrete

Both under-reinforced concrete beams were tested to failure under flexural loading. Table 3 shows the experimental and predicted values for the ultimate moments for the reinforced concrete beams with normal weight concrete and polystyrene aggregate concrete. The ultimate moment for the beams was predicted using the rectangular stress block analysis in AS3600 (7). The results showed that the AS3600 can be employed to yield a conservative estimate of the ultimate moment capacity of under-reinforced polystyrene concrete beams.

It was observed that there was no longitudinal slipping in of the tensile reinforcements at both ends of the polystyrene aggregate concrete beam during the entire stage of loading, indicating the existence of adequate concrete-steel bond.
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Figs. 4 and 5 show the predicted deflections and the measured maximum deflections for RC beam with normal weight aggregate and polystyrene aggregate concrete, respectively. The short-term deflection for the normal weight reinforced concrete beam was calculated using the

**Fig. 4** Moment-Deflection Relationship for Normal Weight Concrete RC Beam

**Fig. 5**: Moment-Deflection Relationship for Polystyrene Concrete RC Beam
simplified method in AS3600 (7) which takes into account the effect of tension stiffening through the use of the following Branson equation.

\[ I_{ef} = I_{cr} + (I_g - I_{cr}) \left( \frac{M_{cr}}{M} \right)^3 < I_g \]

The results show that within the service load range, AS3600 simplified method yields a reasonably close and conservative estimate for the maximum deflection for the normal weight RC beam.

Although the simplified method predicts the actual deflections of the polystyrene concrete beam accurately for the lower load range, it under-estimates the deflection for a part of the service load range. It may be possible that the higher shrinkage of polystyrene concrete compared to normal concrete has resulted in greater initial tensile stresses in the reinforced beam. Subsequent loading causes more severe cracking in the beam so that Branson’s equation over-estimates the tension stiffening effect. Perhaps it is safer to use the following Rangan's (8) modification of Branson's equation to calculate the maximum deflection for the reinforced concrete beam with the polystyrene aggregate concrete.

\[ I_{ef} = I_{cr} + (I_g - I_{cr}) \left( \frac{M_{cr}}{M} \right)^3 \leq 0.6 I_g \]

Calculations of deflections using Rangan's modification of Branson's equation are plotted in Fig. 5 to compare with the actual deflections of the polystyrene concrete beam. It is seen that Rangan's modification yields accurate and conservative values in the working load range. Fig. 6 compares the deflections for the normal-weight concrete and the polystyrene concrete beams.

Fig. 6: Moment-Deflection Relationships for Polystyrene Concrete and Normal-Weight Concrete RC beams
Although the strength of both types of concrete and reinforcement details for both RC beams were similar, the RC beam with PAC deflected considerably more than the corresponding RC beam with normal-weight concrete. This is partly due to the lower static modulus for PAC compared to normal weight concrete, as seen in Table 2.

Fig. 7: Maximum Crack Width - Normal Weight Concrete RC Beam

Fig. 8: Maximum Crack Width for Polystyrene Concrete RC Beam

Cracking of Reinforced Concrete Beams
As expected the cracks in the flexural span were vertical and the length of increased gradually with the increase in the load after the formation of the first crack. Outside the flexural zone, inclined cracks were observed. Figs. 7 and 8, show the observed maximum crack widths using the microscope, for the normal concrete and polystyrene concrete beams during loading. The predicted crack widths using Gergely-Lutz equation are also plotted in these figures for comparison. Although it was expected that the maximum crack widths for the polystyrene RC beam at corresponding stages of loading would be higher than those of the normal concrete beam due to the less uniform nature of polystyrene concrete, there appeared to be no significant difference between the size of the observed maximum crack width of both types of beams.

Furthermore, the Gergely-Lutz equation, adopted in ACI 318 Code (9) and in BS 8110 (10), yields reasonably accurate and conservative estimate of maximum crack widths for both RC beams, especially in the service load range. However it is important to pointed out that, due to the random nature of cracking in concrete beams, more tests should be carried out before recommendation can be made to use the Gergely-Lutz equation on crack width calculations for polystyrene concrete beams.

**CONCLUSIONS**

Based on the results of this experimental investigation on the flexural behaviour of reinforced concrete beams with normal weight and polystyrene aggregate concretes, the following conclusions are made:

(a) The short-term deflection of the reinforced polystyrene concrete beam is higher than that for the similar beam with normal weight concrete.

(b) The moment carrying capacities for reinforced normal weight and polystyrene concrete beams are similar. The rectangular stress block analysis based on AS3600 can be used to provide a fairly accurate and conservative estimate for the moment capacity of the beams.

(c) AS3600 **simplified method** over-estimated the effect of tension stiffening for the polystyrene concrete beam. However, if the prediction equation is modified according to Rangan's suggestion, then it can be applied to the polystyrene concrete beam.

(d) There is no significant difference in the maximum crack width between the beam with normal weight concrete and that with the polystyrene concrete.

(e) Gergely-Lutz equation for estimating maximum crack width may be applied to the reinforced polystyrene concrete beam as well as normal-weight concrete beam.

**REFERENCES**

9. ACI Committee 318, Building Code Requirements for Reinforced Concrete ACI 318-83, American Concrete Institute, Detroit, USA, 1983.