ARCHING ACTION IN STEEL REINFORCED SELF-COMPACTING CONCRETE SLABS

Su E. Taylor (1), Mohammed Sonebi (1), David Kidd(1) and Will McCord(1)

(1) School of Planning, Architecture and Civil Engineering, Queen’s University of Belfast, Belfast, UK

Abstract

Enhanced sustainability can be achieved through an integrated approach and by adopting innovations in technologies as well as by avoiding over-complex and high-energy-consuming solutions in design and construction. It has been recognised for some time that laterally restrained slabs exhibit strengths far in excess of those predicted by most design codes. This enhancement in slab strength is due to Compressive Membrane Action (CMA). Previous research has also shown that CMA has a beneficial influence on the service behaviour of laterally restrained slabs. Therefore, by utilising the benefits of energy saving and waste reducing self-compacting concrete (SCC) in combination with design using CMA, it should be possible to produce more economic and durable concrete slabs with improved whole life performance.

This paper presents the results of laboratory tests on laterally restrained SCC slabs reinforced with steel bars. Arching action is generally governed by a compressive failure hence the main variable was the concrete compressive strength. Two types of supplementary materials limestone powder and ground granulated blast furnace slag were used in producing two grades of SCC. The failure loads of the slabs have been compared to predicted strengths using an arching theory developed at Queen’s University Belfast and with the UK Highways Agency Standard BD81/02 which came about as a result of this research. The arching theory has been extended to incorporate the properties of SCC.

1. INTRODUCTION

An engineering-based approach is essential for transforming the potential of “enabling technologies” into practice. The development of the concept of ‘Sustainable construction’ is aimed at ensuring more-economical use of finite raw materials and reducing, or mitigating against, the accumulation of pollutants and waste. Reuse and recycling of materials and components achieve a rate of over 80% in some Organisation for Economic Co-operation and Development (OECD) countries, but it should be noted that much of the material is used in low-value-added forms. Increasing use of recycled waste for structural applications is one way of positively addressing such sustainability impacts.
SCC was first proposed in 1986 of addressing poor durability of structures in Japan [1]. A lack of skilled workers resulted in insufficient compaction within many structures leading to poor durability. The introduction of SCC into concrete construction can be considered as the most significant advance in concrete technology for decades. SCC is also considered to be the most rapidly emerging technologies in concrete. SCC is a material that meets a unique combination of performance and uniformity requirements that cannot always be achieved using conventional constituents and usual construction practices. The development of SCC marks an important milestone in improving the product quality and efficiency of the building industry [2]. SCC improves the efficiency at the construction sites, enhances the working conditions, the durability and engineering performance, and the quality and appearance of concrete.

Since its proposal, much of the research into the further development of SCC has been carried out in to investigate the fresh properties, the hardened properties, and the durability [2-6]. The structural behaviour of columns and beams cast with SCC has been reported in the literature review [7-10].

Low to medium span bridges constitute the vast majority of road infrastructure bridges in service across the world – whether it be for overpasses/underpasses for motorways or for minor river crossings. Within this category of bridges concrete deck slabs are widely used whether in combination with pre-cast pre-stressed concrete beams or steel girders. Over the past twenty years it has been found that many concrete bridges have exhibited problems, such as spalling, associated with reinforcement corrosion. Such problems are particularly prevalent in marine environments or where freezing/thawing conditions require the intensive use of salt to prevent the formation of ice. In the latter case the vulnerability of the reinforcement in the deck slab can be exceptionally high. A further problem for bridge deck slabs is the need to carry increased loading such as in new European legislation for traffic loads [11-12].

These deck slabs would in many cases be found to be unsatisfactory were it not for an inherent strength which is not taken into account in normal flexural design approaches. In particular it is accepted that the capacity of the slab elements of beam and slab decks is greatly enhanced due to the restraint provided by the beams and diaphragms. This enhancement has been recognised by a number of bridge authorities worldwide by incorporating it into their national design codes. Whilst BS5400 [13] does not recognise this, the current UK assessment codes [11-12] for concrete structures do allow arching action to be included in the assessed capacity of deck slabs. The recognition of arching action is most important as it can mean the difference between a bridge deck passing or failing the assessment requirements. In this paper the greatly enhanced strength associated with arching action, which is clearly of benefit for increased loadings, when taken into account in the design process can be shown to produce concrete bridge decks which are more durable than current designs. Any associated increases in costs will be more than compensated for by the anticipated increase in life expectancy before repairs are needed.

The advent of Johansen’s [14] yield line theory in the 1940s led designers and researchers to believe that at long last they had a prediction method for slabs which would provide realistic strength estimates. However, the tests carried out by Ockleston [15] on interior panels of the old dental hospital in Johannesburg revealed collapse loads of four times those predicted by the yield line method. This enhanced capacity was attributed to the development of an internal arching mechanism arising from the restraining effect of the
surrounding panels. Where a slab is restrained against longitudinal expansion, an arching thrust develops, Fig. 1. With the development of tension cracks at mid-span and at the supports the beam tries to expand longitudinally but as it is restrained, corresponding forces are induced which allow it to sustain a substantial load on the basis of the arching thrusts which develop as the deformation increases.

This phenomenon occurs when vertically loaded slabs are restrained against horizontal expansion and is generally referred to as compressive membrane action (CMA). The extent of the enhancement provided by compressive membrane action, over and above the flexural strength, depends on the degree of restraint provided by the surrounding structure and the concrete compressive strength. A small number of codes have recognized the benefits of CMA; these include the department of regional development (NI), ‘Design Specification For Bridge Decks’. The Canadian Bridge Design Code and the UK Highways Agency Standard, BD81/02 which came about as a result of research at Queen’s University Belfast.

The bending capacity of an unrestrained concrete slab strips is affected primarily by the amount and strength of the reinforcement and only marginally by the concrete strength. In contrast, laterally restrained slab strips generally fail by crushing of the concrete at the hinges and so the capacity is significantly influenced by the concrete compressive strength. Previous research [16] led to the development of an arching theory for assessing the strength of laterally restrained one-way spanning slab strips. This research showed that the strength of laterally restrained slabs is sensitive to the degree of external lateral restraint. A second series of tests [17] were carried out on scaled bridge deck edge panels which replicated the degree of external lateral restraint in a typical bridge deck slab in practice. It was concluded that the enhanced strength and serviceability of laterally restrained slabs can be taken into account in the assessment bridge deck slab to provide development of highly durable deck slabs, which will be virtually maintenance free.

The research presented in this paper extends the previous research in CMA to further enhance the sustainability of bridge deck slabs by incorporating SCC. The SCC incorporated limestone powder (LSP) or ground granulated blast furnace slag (GGBS) to produce two grades of normal strength C40 and high strength C60. Additionally, the material properties for the arching theory have been adapted to include SCC.
2. EXPERIMENTAL INVESTIGATION

2.1 Materials and mix proportions

The concrete mixes investigated in this study were prepared with portland cement (PC), LSP, or GGBS. Class 42.5 cement was used in this study. The cement and GGBS used conformed to Standard BS EN 197-1 CEM1 and BS6699. The chemical and physical properties of cement, LSP and GGBS are presented in Table 1. The content of CaCO₃ in limestone powder was greater than 97%, the sieve residue >125μm is 15%, and the sieve residue > 63μm is 30%, the specific gravity is 2700 kg/m³.

Continuously graded crushed gravel aggregate with a nominal particle size of 20 mm and 10 mm were used, their particle distributions are shown in Figure 1. Well-graded quartzite sand with a fineness modulus of 2.60 was employed; the particle distribution is shown in Figure 2. The relative density values of the coarse aggregate and sand were 2.75, 2.70 and 2.50, and their water absorption rates were 0.7%, 1.0% and 0.4% respectively. SP based on chains of modified polycarboxylic ether was used and had 40% solid content and specific gravity of 1.08.

As the main of the variable was the concrete compressive strength, both a normal C40 and high C60 strength SCC were required for the test models. Optimisation of the SCC mixes required several trial mixes to achieve the required filling ability, passing ability, resistance to segregation and compressive strength. The mixes were also designed to conform to the requirements in the European guidelines for Self Compacting Concrete. The two selected mix proportions of SCC40 and SCC60 are summaries in Table 1.

Table 1. Chemical and physical properties of cementitious materials

<table>
<thead>
<tr>
<th></th>
<th>Cement</th>
<th>Limestone powder</th>
<th>GGBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>20.8</td>
<td>2.8</td>
<td>33.5</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>5.7</td>
<td>0.3</td>
<td>13.6</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.6</td>
<td>0.06</td>
<td>0.62</td>
</tr>
<tr>
<td>CaO</td>
<td>64.4</td>
<td>54.3</td>
<td>42.7</td>
</tr>
<tr>
<td>MgO</td>
<td>1.9</td>
<td>0.2</td>
<td>6.5</td>
</tr>
<tr>
<td>Na₂O eq.</td>
<td>0.39</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Free CaO</td>
<td>1.64</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>LOI</td>
<td>---</td>
<td>97</td>
<td>0.67</td>
</tr>
<tr>
<td>CaCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative Density</td>
<td>3.14</td>
<td>2.7</td>
<td>2.90</td>
</tr>
<tr>
<td>Blaine (m²/kg)</td>
<td>385</td>
<td>--</td>
<td>460</td>
</tr>
</tbody>
</table>
The slump flow test, V-funnel test, L-box test, and settlement segregation column test were used to evaluate filling ability, passing ability and segregation of SCC [18]. The resistance to segregation was measured by the column segregation test made with a PVC column divided into 3 equal sections having diameter 190 mm and height of 170 mm clamped together with circular metal clamps and was filled with concrete and left to rest for 15 min.

### 2.2 Test slabs and test arrangement

The slabs were made according to the trial mix results and the steel reinforcing bars were deformed high yield 12mm diameter bars with yield strength of 503N/mm². Nine cubes and three cylinders were taken from each batch concrete for material testing to determine the compressive and tensile strengths for the self compacting concrete. After 2 days the slab was demoulded, covered with wet hessian cured for 28 days until the load test. A line load was applied across the midspan of each test slab and the loading arrangement is shown in Fig.2. Loading was applied through a stiff loading beam with a 25mm knife edge loading plate welded to the bottom flange. End restraint was provided by a self-straining stiff steel frame. To ensure a fully encastre support provision was made for bolting through the depth of the slab at each end. Electronic displacement transducers were located directly below the position of the knife edge load on each side of the slab soffit and at the restraint system to measure horizontal movement at each end of the rig. In each of the test slabs, two preliminary test loads of approximately 40% of the estimated failure load were applied and held for 5 minutes and the recovery measured. The test slab was then loaded to failure. The development of cracking was monitored throughout the test.

<table>
<thead>
<tr>
<th>Materials</th>
<th>SCC40 (kg/m³)</th>
<th>SCC60 (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>320</td>
<td>330</td>
</tr>
<tr>
<td>LSP</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>GGBS</td>
<td>--</td>
<td>200</td>
</tr>
<tr>
<td>Water</td>
<td>182</td>
<td>154</td>
</tr>
<tr>
<td>CA. 20mm</td>
<td>565</td>
<td>535</td>
</tr>
<tr>
<td>CA. 10mm</td>
<td>290</td>
<td>275</td>
</tr>
<tr>
<td>Sand</td>
<td>920</td>
<td>1000</td>
</tr>
<tr>
<td>SP</td>
<td>3.0</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Table 2: Mix Proportions of SCC mixes
3. EXPERIMENTAL RESULTS AND DISCUSSION

The results of fresh properties are summarised in Table 3. Both SCC mixes demonstrated a good filling ability, passing ability and segregation resistance. These mixes can be classified, according the European guidelines for SCC, the slump flow as SF1, V-funnel as VS2/VF2, and PA1 for L-box test. The settlement segregation ratio can be considered a good.

Table 3: Fresh properties of SCC mixes

<table>
<thead>
<tr>
<th></th>
<th>SCC40</th>
<th>SCC60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump flow (mm)</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>V-funnel (s)</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>L-box blocking ratio</td>
<td>0.80</td>
<td>0.95</td>
</tr>
<tr>
<td>Segregation ratio</td>
<td>0.91</td>
<td>0.89</td>
</tr>
</tbody>
</table>

3.1 Load test results and discussion

A summary of the failure loads and concrete strengths at the time of testing are given in Table 4. The first crack in all the test slabs initiated in the midspan region directly under the line load. In both tests, this crack extended upwards towards the loaded face and widened to between 2.5mm and 3mm at the maximum load. Failure then occurred by crushing in the compression zone. The slab restraint enabled the development of a negative support moment. This was highlighted by the development of tension cracks in the top face of the. In test slab 2 with higher concrete compressive strength these cracks developed at higher loads. The results of applied load vs. vertical deflection at midspan are shown in Fig. 3 for both of the test slabs. The horizontal displacement at the end of the rig was low indicating sufficient lateral restraint. The crushing in the compression zone became more pronounced in the slab with higher concrete strengths, exhibiting behaviour similar to an over reinforced slab. The increase in capacity with increasing concrete strength and the evidence of high compressive forces characterised by concrete crushing between the end plate and the...
end of the slab, in addition to the compression zones below the load point, indicated the development of CMA. It can be seen from Fig. 3 that the high strength SCC60 (S-72-LR) slab exhibited a higher ultimate capacity despite the same percentage reinforcement as the normal strength SCC40 (S-41-LR) slab. Additionally, the S-72-LR slab showed improved service performance beyond an applied load of 120kN and had a smaller deflection at ultimate load compared to the S-41-LR slab.

Table 5: Test slab results and predicted strengths

<table>
<thead>
<tr>
<th>Slab</th>
<th>SCC cube compressive strength, $f_{cu}$ (MPa)</th>
<th>SCC tensile strength, $f_t$ (MPa)</th>
<th>Failure Load (kN)</th>
<th>Deflection at Failure (mm)</th>
<th>Predicted flexural capacity (kN)</th>
<th>Predicted capacity using QUB arching theory (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-41-LR</td>
<td>45.7</td>
<td>2.7</td>
<td>165</td>
<td>21.2</td>
<td>69.2</td>
<td>137</td>
</tr>
<tr>
<td>S-72-LR</td>
<td>72.3</td>
<td>4.9</td>
<td>180</td>
<td>17.3</td>
<td>72.0</td>
<td>172</td>
</tr>
</tbody>
</table>

Figure 3: Test results for midspan deflection vs. applied load for the failure tests

3.2. Modification to current arching theory

Rankin and Long [17] developed a method for predicting the enhanced punching strength of slab and column specimens under compressive membrane (or arching action). The theory for the prediction of ultimate capacity was based on the deformation theory of McDowell et al [19]. The effect of arching and bending were considered separately, although in reality the compressed concrete is due to both the action of arching and bending. This arching analysis was further developed by Taylor et al. [20] to incorporate concrete with high compressive strengths (>70MPa). The theory for the prediction of the arching capacity uses the deformation theory of McDowell et al [19]. The effect of arching and bending were considered separately, although in reality the compressed concrete is due to both the action of arching and bending. The procedure for assessing the strength of laterally restrained slabs can be outlined by the following calculation flow diagram:
The arching section can be described as the depth available for arching and depends upon the depth of the compression zone due to flexure. The depth available for arching, $2.d_1 = h - 2x.\beta$ [Eqn.1]

The contact area due to arching is then given by: $A = \alpha.b.d_1$ [Eqn.2]

and to take into account the less than rigid restraint, an ‘equivalent’ rigidly restrained arch length, $L_r$, is used:

$$L_r = L_e \left( \sqrt{\frac{E_c A}{KL_c}} \right) + 1$$ [Eqn.3]

The ratio of the slab stiffness to the external lateral restraint has an effect on the degree of arching action and it was necessary to use an accurate prediction for the elastic modulus. The previous work with high performance concrete [15] used the following relationship between the concrete compressive strength and the modulus of elasticity:

Where: $E_c = 4.23 f_{ck}^{0.5} \text{kN/mm}^2$ [Eqn.4]

The arching strength has also been predicted using the ACI relationship:

Where: $E_c = 3.32 f_{ck}^{0.5} + \left( \frac{\rho}{2346} \right)^{1.5} \text{kN/mm}^2$ [Eqn.5]

and

$\rho = 2450\text{kg/m}^3$

And the CEB/FIP Model Code 90:

Where: $E_c = 10(f_{ck}^{0.5} + 8)^{0.333} \text{kN/mm}^2$ [Eqn.6]
The predicted strength using arching theory are given in Table 5 and it can be seen that the arching theory gives a far better estimate for the ultimate capacity compared to standard flexural theory. The predicted arching strength was more accurate for the S-72-LR slab (high SCC strength) compared to the S-41-LR slab (normal SCC strength) and both predictions were conservative. Table 6 also gives the effect of varying the elastic modulus for the predictions using arching theory and it can be seen that the ACI and CEB equation gave an unsafe prediction for the S-72-LR slab which suggests that the prediction for the elastic modulus was too stiff for the high strength SCC. Further research is required to establish a valid prediction for the elastic modulus for high strength SCC.

Table 6: Comparison of predicted strengths using arching theory and different values of elastic modulus

<table>
<thead>
<tr>
<th>Slab</th>
<th>Failure load (kN)</th>
<th>Predicted capacity QUB arching theory using Eqn.4 – QUB (kN)</th>
<th>Predicted capacity QUB arching theory using Eqn.5- ACI (kN)</th>
<th>Predicted capacity QUB arching theory using Eqn.6 - CEB (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-41-LR</td>
<td>165</td>
<td>137</td>
<td>136</td>
<td>132</td>
</tr>
<tr>
<td>S-72-LR</td>
<td>180</td>
<td>172</td>
<td>185</td>
<td>187</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

The primary aim of this research was to extend the existing knowledge of arching action in laterally restrained slabs made with SCC and to adapt the material properties in the arching theory to encompass SCC. From experimental and analytical studies the following conclusions have been drawn:-

1. Two types of SCC mixes incorporating different supplementary materials were used successfully in the bridge deck slab strips and no external vibration was required in the casting of the slabs.
2. The experimental observations were consistent with the development of compressive membrane action in the laterally restrained SCC slabs.
3. The ultimate strength of the laterally restrained slabs was more dependent on concrete compressive strength than the type of reinforcement.
4. The adapted arching theory gave a more accurate prediction for the slabs compared to standard flexural theory.
NOTATION

- $A_s$: area of steel reinforcement
- $d_1$: half the arching depth
- $E_c$: concrete elastic modulus
- $E_s$: steel elastic modulus
- $K_r$: stiffness of restraint $= 410 \text{kN/mm}^2$
- $K_s$: stiffness of slab
- $L_r$: half the span of the equivalent rigidly restrained arch
- $L_e$: half the span of the arch length
- $x$: depth of concrete in the compression zone
- $\alpha$: proportion of $d_1$ in contact with the support
- $\beta$: proportional depth of stress bloc

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REFERENCES