Durable Continuously Reinforced Concrete Pavements through Active Crack Control

Lambert Houben, Dongya Ren, Anne Beeldens, Luc Rens


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Characteristics Continuous Reinforced Concrete Pavements (CRCP)

Crack pattern measurements (spacing, crack width) on 3 motorways:
- E17 near Ghent (B), no crack control
- A50 near Eindhoven (NL), no crack control
- E313 near Herentals (B), active crack control

Concluding remarks
Characteristics CRCP

- Longitudinal reinforcement 0.7%-0.75%
- Reinforcement mid-depth or higher
- Control shrinkage crack pattern (spacing, width)
- Criteria for reinforcement: crack width < 0.4 mm (NL,B)
- No transverse joints
- Increasingly applied in Europe (especially Belgium) and USA on heavily loaded motorways
Characteristics CRCP

Pavement structure (reconstruction E17 in Belgium in 2011), dimensions in cm

- Reinforcement
- Asphalt interlayer
Characteristics CRCP

Longitudinal reinforcement (e.g. Ø 20 mm @ 180 mm)
**Characteristics CRCP**

Minimum percentage of longitudinal reinforcement to prevent yield of rebars

<table>
<thead>
<tr>
<th>Concrete grade</th>
<th>C25/30</th>
<th>C30/37</th>
<th>C35/45</th>
<th>C45/55</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_{0,\text{min}}$</td>
<td>0.38</td>
<td>0.43</td>
<td>0.47</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Practical percentage of longitudinal reinforcement (in North-west Europe)

<table>
<thead>
<tr>
<th>Concrete grade</th>
<th>C25/30</th>
<th>C30/37</th>
<th>C35/45</th>
<th>C45/55</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_0$</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.75</td>
</tr>
</tbody>
</table>
CRCP investigations

Investigations into crack pattern:
- **E17** near Ghent, Belgium:
  - reconstruction in August 2011
  - no active crack control
- **E313** near Herentals, Belgium:
  - reconstruction in September 2012
  - active crack control
- **A50** near Eindhoven, the Netherlands:
  - 8 years old, 70 mm twinlayer PA wearing course
  - no active crack control
  - reflective cracking in PA wearing course
CRCP on E17 near Ghent (no crack control)

3 test sections

<table>
<thead>
<tr>
<th>Test section</th>
<th>Chainage (km)</th>
<th>Longitudinal reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>44.7 - 45.2</td>
<td>0.75%</td>
</tr>
<tr>
<td>2</td>
<td>45.2 - 46.2</td>
<td>0.70%</td>
</tr>
<tr>
<td>3</td>
<td>46.2 - 46.7</td>
<td>0.65% + 20 kg/ m³ steel fibers</td>
</tr>
</tbody>
</table>

Crack pattern (spacing and width) measurements:
- regularly during 4 days and nights after construction in August 2011
- 5 times in period October 2011 – April 2014
CRCP on E17 near Ghent (no crack control)

Crack width measurements at pavement surface
CRCP on E17 near Ghent (no crack control)

Change of crack width measurements ad pavement edge
(LVDT measurements on glued studs across crack)
CRCP on E17 near Ghent (no crack control)

Typical cracks

Y-cracks

Cluster of closely spaced cracks
CRCP on E17 near Ghent (no crack control)

Development of crack pattern

(a) 0.75%
(b) 0.70%
(c) 0.65% and steel fiber
CRCP on E17 near Ghent (no crack control)

Development of crack spacing

![Graphs showing development of crack spacing over time with different crack control measures.]
CRCP on E17 near Ghent (no crack control)

Development of crack width at pavement surface in section 1

<table>
<thead>
<tr>
<th>Age (days)</th>
<th>Temperature at pavement surface (°C)</th>
<th>Number</th>
<th>Crack width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>cracks</td>
<td>readings</td>
</tr>
<tr>
<td>4</td>
<td>30.3</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>223</td>
<td>8.8</td>
<td>14</td>
<td>42</td>
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</tbody>
</table>
**CRCP on E17 near Ghent (no crack control)**

Crack width changes at pavement edge in test section 1, 3 days after construction

<table>
<thead>
<tr>
<th>Depth below pavement surface (mm)</th>
<th>Temperature change (°C)</th>
<th>Crack number</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>22.0-30.2</td>
<td>0.132</td>
<td>0.202</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>0.136</td>
<td>0.212</td>
</tr>
<tr>
<td>90*</td>
<td></td>
<td>0.131</td>
<td>0.178</td>
</tr>
</tbody>
</table>

* Centre of longitudinal reinforcement
CRCP on E17 near Ghent (no crack control)

Risk of closely spaced cracks: punchouts

Early 2015 1 punchout observed in wheel track of test section 3 (0.65% + 20 kg/m³ steel fibers)
CRCP on A50 near Eindhoven (no crack control)

70 mm twinlineer PA wearing course on CRCP

8 years after construction: reflective cracking
CRCP on A50 near Eindhoven (no crack control)

100 m section, air temperature 5°C (November 2013), pavement age 8 years, 0.67% longitudinal reinforcement

Crack pattern:
- average crack spacing 1.92 m (large!)
- 27% of crack spacings ≤ 0.6 m (a lot)
- 41% of crack spacings 0.6 – 2.4 m
- 32% of crack spacings ≥ 2.4 m (a lot!)
- 15 out of 52 cracks (30% ) reflected through PA
CRCP on A50 near Eindhoven (no crack control)

Cores taken on 9 cracks for crack width measurements

<table>
<thead>
<tr>
<th>Core number</th>
<th>Crack width (mm)</th>
<th>Sum of crack spacings at both sides of the crack (m)</th>
<th>Reflective crack</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>top</td>
<td>middle</td>
<td>bottom</td>
</tr>
<tr>
<td>1</td>
<td>0.35</td>
<td>0.25</td>
<td>0.35</td>
</tr>
<tr>
<td>2</td>
<td>0.23</td>
<td>0.30</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>0.29</td>
<td>0.10</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>0.55</td>
<td>0.30</td>
<td>0.41</td>
</tr>
<tr>
<td>5</td>
<td>0.35</td>
<td>0.30</td>
<td>0.30</td>
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<tr>
<td>6</td>
<td>0.18</td>
<td>0.18</td>
<td>0.20</td>
</tr>
<tr>
<td>7</td>
<td>0.20</td>
<td>0.17</td>
<td>0.29</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>0.28</td>
<td>0.34</td>
</tr>
<tr>
<td>9</td>
<td>0.32</td>
<td>0.26</td>
<td>0.33</td>
</tr>
<tr>
<td>average</td>
<td>0.31</td>
<td>0.24</td>
<td>0.31</td>
</tr>
</tbody>
</table>

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CRCP on A50 near Eindhoven (no crack control)

Cores taken on 9 cracks for crack width measurements

To prevent reflective cracks in this specific case:
- crack width < 0.25 mm
- sum of crack spacings < 3.2 m, i.e. crack spacings < 1.6 m

Mid 2014 (age 9 years) PA milled off and replaced by SAMI plus 70 mm twinlayer PA
CRCP on E313 near Herentals (crack control)

Reconstruction in 2012
2-lift concrete pavement (50 mm + 200 mm = 250 mm)
Longitudinal reinforcement 0.75%, 90 mm below pavement surface
50 mm asphalt interlayer

Trial to control crack pattern through surface notches (short transverse saw cuts), applied within 16 hours after construction
CRCP on E313 near Herentals (crack control)

Top view
CRCP on E313 near Herentals (crack control)

Geometry of notches

- **Spacing**: 1.2 m
- **Length**: 0.4 m
- **Depth**: 30 or 60 mm
CRCP on E313 near Herentals (crack control)

<table>
<thead>
<tr>
<th>Depth of saw cut (mm)</th>
<th>Section length (m)</th>
<th>Age (days)</th>
<th>No. of notches (N1)</th>
<th>No. of cracks (N2)</th>
<th>No. of cracks at notches (N3)</th>
<th>Effectiveness of notches N3/N1 (%)</th>
<th>Percentage of cracks in category (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Distance to nearest notch (m)</td>
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<td></td>
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<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.1</td>
<td>0 (N3/ N2)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>73</td>
<td>71</td>
<td>0.1</td>
<td>0-0.2</td>
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<td>3</td>
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<td>161</td>
<td>7.9</td>
<td>0.2-0.4</td>
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<td>4</td>
<td>193</td>
<td>191</td>
<td>17.9</td>
<td>0.4-0.6</td>
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<td></td>
<td></td>
<td></td>
<td>65</td>
<td>664</td>
<td>555</td>
<td>21.3</td>
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<td></td>
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<td>204*</td>
<td>762</td>
<td>597</td>
<td>61.9</td>
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<td>378</td>
<td>775</td>
<td>606</td>
<td>66.6</td>
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<td></td>
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<td></td>
<td>555**</td>
<td>803</td>
<td>628</td>
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<td>70.0</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>123</td>
<td>245</td>
<td>58.1</td>
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<td>417</td>
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<td></td>
<td>3</td>
<td>497</td>
<td>286</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>505</td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

* after 1st winter

** after 2nd winter

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CRCP on E313 near Herentals (crack control)

**Straight cracks**

- Crack at notch
- Crack in between 2 notches
CRCP on E313 near Herentals (crack control)

Crack spacing frequency distributions

- E313 60 mm
- E313 30 mm

Cumulative percentage vs. crack spacing (m)

Days:
- 4 days
- 65 days
- 204 days
- 378 days
- 555 days
- 123 days
- 262 days
- 436 days
- 613 days
Comparison crack pattern on E17 and E313

Crack spacing after about 20 months (including 2 winters) on E17 and E313, 0.75% reinf.

- Mean crack spacing
- Crack spacing frequency distribution
## Comparison crack pattern on E17 and E313

Crack spacing after about 20 months (including 2 winters) on E17 and E313, 0.75% reinforcement

<table>
<thead>
<tr>
<th>Motorway</th>
<th>Test section</th>
<th>Crack spacing distribution (%)</th>
<th>Average crack spacing (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>≤ 0.6 m</td>
<td>0.6 - 2.4 m</td>
</tr>
<tr>
<td>E17</td>
<td>1</td>
<td>51.8</td>
<td>29.4</td>
</tr>
<tr>
<td>E313</td>
<td>60 mm notches 30 mm notches</td>
<td>14.0</td>
<td>75.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29.6</td>
<td>65.9</td>
</tr>
</tbody>
</table>
## Comparison crack pattern on E17 and E313

Crack width changes due to temperature on E17 and E313, 0.75% reinforcement

<table>
<thead>
<tr>
<th>Motorway</th>
<th>Test section</th>
<th>Temperature of pavement surface (°C)</th>
<th>Number of cracks</th>
<th>Crack width (mm)</th>
<th>standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>E17</td>
<td>1</td>
<td>30.3</td>
<td>8</td>
<td>0.169</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.2</td>
<td>10</td>
<td>0.312</td>
<td>0.35</td>
</tr>
<tr>
<td>E313</td>
<td>60 mm notches</td>
<td>20.5</td>
<td>17</td>
<td>0.152</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.0</td>
<td>12</td>
<td>0.201</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>30 mm notches</td>
<td>21.0</td>
<td>11</td>
<td>0.198</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.2</td>
<td>11</td>
<td>0.232</td>
<td>0.32</td>
</tr>
</tbody>
</table>
Concluding remarks

Active crack control through partial surface notches seems quite successful:
- Less closely spaced cracks and less widely spaced cracks
- So more crack spacings in preferred range 0.6 – 2.4 m
- Very straight cracks (not interfering)
- Cheap measure

But:
- Only 3 years of experience
- Time of saw cutting partial surface notches very important (current practice: within 16 hours of concrete placement)
Delft

Muito obrigado
Types of concrete pavements

1. Jointed plain concrete pavements (JPCP):
   - Through joints divided into slabs, 5 * 4 m
   - Dowel and tie bars in transverse and longitudinal joints, resp.
   - Joints mostly sealed
   - No reinforcement at all
   - Most widely applied
   - Empirical and analytical design methods
Empirical design method: RStO 11 (Ger)

RStO 11 (Germany)

Only JPCP

type of base

traffic loading

<table>
<thead>
<tr>
<th>R</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
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<tbody>
<tr>
<td>&gt; 32</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>&gt; 10 - 32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 3.2 - 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>&gt; 1.8 - 3.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 1.0 - 1.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 0.3 - 1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>≤ 0.3</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Analytical design method: VENCON2.0 (NL)

1. Traffic loadings:
   Axle loads
   Directional factor
   Design traffic lane
   Traffic at joints

2. Climate:
   Temperature
   Gradients

3. Substructure:
   Modulus of substructure reaction

4. Concrete:
   Strength parameters
   Elastic modulus

5. Traffic load stresses:
   Load transfer at joints
   Westergaard equation

6. Temperature gradient stresses:
   Eisenmann/Dutch method

7. Thickness plain/reinforced pavement:
   Miner fatigue analysis

8. Additional checks plain pavements:
   Robustness (NEN 6720)
   Traffic-ability at opening

9. Reinforcement of reinforced pavements:
   Shrinkage and temperature
   Tension bar model
   Crack width criterion

10. Additional checks reinforced pavement:
    Robustness (NEN 6720)
    Traffic-ability at opening
    Parameter studies
Types of concrete pavements

2. Pre-stressed concrete pavements:
   - Large slabs, 130 * 30 m
   - Pre-stressed in 2 directions
   - Thin pavement (airport: 180 mm)
   - Very complex joints
   - Most expensive type of pavement
   - Few applications (Amsterdam Airport Schiphol)
Types of concrete pavements

Amsterdam Airport Schiphol (55 million passengers/year)

- JPCP (new), up to 420 mm thick
- Prestressed (old), 180 mm thick
- Platforms on airport
  Rio de Janeiro?
CRCP on A5 near Amsterdam (no crack control)

50 mm single layer PA wearing course on CRCP

13 years after construction: reflective cracking
CRCP on A5 near Amsterdam (no crack control)

Three 100 m sections, air temperature 2°C-5°C (February 2015), pavement age 13 years, 0.60% longitudinal reinforcement

Crack pattern:
- average crack spacing 4.41 m (very large!!)
- 5% of crack spacings ≤ 0.8 m
- 29% of crack spacings 0.8 - 3.0 m (very few!)
- 66% of crack spacings ≥ 3.0 m (an awful lot!)
- 39 out of 68 cracks (57% !) reflected through PA
## CRCP on A5 near Amsterdam (no crack control)

### Crack width characteristics at pavement surface (37 cracks)

<table>
<thead>
<tr>
<th>Crack width parameter</th>
<th>With reflective cracks</th>
<th>Without reflective cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cracks</td>
<td>24</td>
<td>13</td>
</tr>
<tr>
<td>Mean crack width (mm)</td>
<td>0.45</td>
<td>0.38</td>
</tr>
<tr>
<td>Standard deviation of crack width (mm)</td>
<td>0.14</td>
<td>0.10</td>
</tr>
<tr>
<td>Maximum crack width (mm)</td>
<td>0.91</td>
<td>0.59</td>
</tr>
<tr>
<td>Minimum crack width (mm)</td>
<td>0.27</td>
<td>0.23</td>
</tr>
</tbody>
</table>
CRCP on A5 near Amsterdam (no crack control)

Crack width characteristics at pavement surface (37 cracks)

The sum of slab length at both sides of a crack (m)

Crack Width (mm)

- Reflective Cracks
- Without Reflective Cracks
### CRCP on A5 near Amsterdam (no crack control)

#### Cores taken on 12 cracks for crack width measurements

<table>
<thead>
<tr>
<th>Crack width parameter</th>
<th>With reflective cracks</th>
<th>Without reflective cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cracks</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Mean crack width (mm)</td>
<td>0.448</td>
<td>0.371</td>
</tr>
<tr>
<td>Standard deviation of crack width (mm)</td>
<td>0.057</td>
<td>0.059</td>
</tr>
<tr>
<td>Maximum crack width (mm)</td>
<td>0.488</td>
<td>0.468</td>
</tr>
<tr>
<td>Minimum crack width (mm)</td>
<td>0.408</td>
<td>0.295</td>
</tr>
</tbody>
</table>
CRCP on A5 near Amsterdam (no crack control)

Cores taken on 12 cracks for crack width measurements

The sum of slab length at both sides of a crack (m)

- Reflective Cracks
- Without Reflective Cracks
- Série1
CRCP on A73 near Echt (no crack control)

70 mm twinlayer PA wearing course on CRCP

8 years after construction: few reflective cracks

- Low-severity reflective crack
- Medium-severity reflective crack
CRCP on A73 near Echt (no crack control)

On Eastern carriageway, 5 sections, total 1500 m, air temperature 10°C → 25°C (April 2015), pavement age 8 years, 0.70% longitudinal reinforcement mid-depth

Crack pattern very good:
- average crack spacing 1.88 m
- 18% of crack spacings ≤ 0.8 m
- 67% of crack spacings 0.8 – 3.0 m
- 15% of crack spacings ≥ 3.0 m
- 15 out of 803 cracks (only 2%!) reflected through PA
CRCP on A73 near Echt (no crack control)

On Western carriageway, 6 sections, total 1062 m, air temperature 9°C → 17°C (April 2015), pavement age 8 years, 0.70% longitudinal reinforcement mid-depth

Crack pattern less good:
- average crack spacing 2.63 m (a bit large)
- 11% of crack spacings ≤ 0.8 m
- 57% of crack spacings 0.8 – 3.0 m
- 32% of crack spacings ≥ 3.0 m
- 27 out of 404 cracks (7.2%) reflected through PA
CRCP on A73 near Echt (no crack control)

Crack width measurements not successful (filled with dust, a bit spalling)

A73 quite good performance:
- crack pattern (near to) optimal
- double tack coat between CRCP and PA
- polymer modified bitumen applied in both top layer and bottom layer of PA (normally only in top layer)
- few reflective cracks, no other damage
- no PA replacement needed in near future
Comparison crack spacings

Comparison of crack spacing frequency distributions: huge differences!