# RECYCLED CONCRETE AGGREGATE IN CONCRETE PAVEMENTS: A FIVE YEAR STUDY ON ITS EFFECT ON PAVEMENT PERFORMANCE


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## ABSTRACT

Recycled Concrete Aggregate (RCA) from demolished concrete is becoming increasingly available. Its use in the construction of new concrete pavements provides both environmental and economic benefits. The recycling of waste concrete as aggregate reduces the demand for virgin aggregates, of which there will be a critical shortage in the future. The use of RCA also protects the landscape and the environment by deferring the need to open new quarries, reducing the impact on landfills and decreasing energy consumption.

Four pavement test sections were constructed in 2007 at the University of Waterloo's Centre for Pavement and Transportation Technology (CPATT) test track facility at the Region of Waterloo's waste management site. The test sections contain varying amounts of RCA in the concrete mix. Instrumentation was embedded in each section to assess the effects of environmental factors, including temperature and moisture gradients, on long-term pavement performance. Each test section was provided with sensors to measure strains, slab curling and warping, joint movement and concrete maturity.

This paper presents a brief overview of the design and construction of the CPATT RCA sections, as well as a five-year performance evaluation of the pavement sections using sensor data and visual condition survey results. To date, comparable performance has been observed in all RCA sections, in comparison to the control section, suggesting that RCA is a suitable component for durable, long-lasting concrete pavements.


## 1. INTRODUCTION

As the demand for construction aggregates is increasing, the availability of quality aggregate is declining. The province of Ontario is experiencing an aggregate shortage, which can worsen in the future years [1]. In fact, in Ontario, aggregates are being used faster than they can be made available [2]. However, significant amounts of waste concrete from demolition activities are also being produced. Consequently, the possibility of replacing a portion of virgin aggregates with Recycled Concrete Aggregate (RCA) is becoming an option for new concrete mixes.

Previous studies have successfully shown that the important solid skeleton of the mixture can be replaced by materials already present on the existing road or from recycling of household or industrial waste [3]. Moreover, the experiences of several transportation agencies have shown that RCA has the potential to produce strong and durable materials, which is suitable for use in road infrastructure [4]. Furthermore, the use of RCA can have both environmental and economic benefits. Construction and demolition waste covers a large portion of all solid waste generated, filling up valuable space in landfills [5]. The use of RCA reduces the need to dispose of waste concrete, promotes the conservation of virgin aggregates and avoids the need to transport the waste from the site to the landfill.

The use of RCA is also cost effective, as it can reduce project costs. The estimated cost reduction from incorporating RCA is up to $10 per tonne of aggregate [6]. Virgin aggregate does not need to be extracted, processed and transported to the site and demolished concrete does not need to be removed from the site and disposed [7]. Since the recycled material can be used within the same metropolitan area, the energy consumption from producing and hauling aggregate is reduced. Additionally, the recovery of steel reinforcement from the recycling process provides further economic and environmental benefits, because the material usually becomes property of the contractor, who can sell it as a scrap metal. The use of RCA in concrete pavements has been successful in the USA and in Canada in the construction of new roads, providing environmental and economic benefits and improving the state of the practice [1].

Previous studies have shown how the use of RCA has the potential to modify some physical and mechanical characteristics of concrete mixtures; however, not all the reported changes can be directly related to the amount of RCA [8]. These effects on concrete properties can affect the long-term performance of the concrete mix. RCA has the greatest potential to reduce the overall durability of RCA concrete, likely due to the greater amount of fissures created by RCA, into which fluids can permeate and diffuse [9]. Scientific literature, however, is still not unanimous about the effects of RCA content on concrete performance, so much research is still needed to answer questions.

Also, it is important to consider that climate can affect long-term pavement performance of pavement too, especially in Southern Ontario, where severe freeze thaw cycles and wide temperature fluctuations can occur [10]. To evaluate the impact of RCA content on the characteristics of concrete mixes in pavement applications, it is necessary to evaluate the responses and performance of RCA concrete pavements in the long-term through field studies.

## 2. OBJECTIVE AND SCOPE

The Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo, in collaboration with the Natural Sciences and Engineering Research Council of Canada (NSERC), the Cement Association of Canada, Dufferin Construction and Holcim (Canada) Inc., began a research project in 2007 to study the effects of RCA on the performance of concrete pavements.

The objective of this research project was to evaluate the long-term performance of concrete pavements with different percentages of RCA through the construction of full scale test sections that was instrumented with various sensors to analyze and monitor pavement responses over time.

Four different sections, each with a different RCA content, ranging from 0% to 50%, were constructed in 2007 and data from the embedded sensors have been collected for five years. The sensor data permits researchers to evaluate and quantify how climactic effects impact the behaviour and the performance of the sections.

By varying the RCA of each section, it is possible to assess if and how the RCA content impacts pavement performance. One of the four sections contains 0% RCA and it can be considered as a control section, representing a conventional concrete mix, but is subjected to the same traffic loadings and environmental conditions as the RCA sections.

# 3. TEST TRACK DESCRIPTION, SENSOR PLACEMENT AND LOCATION

The CPATT test track is located in the Region of Waterloo Waste Management Site. The test track is a full-scale accelerated research facility, 1294 m long and 8 metres wide. This test road allows researchers to monitor the performance of various asphalt and concrete mixes in the Canadian environment under heavy truck loadings.

The traffic travelling on the test track is almost entirely composed of heavy vehicles. It is estimated that 33,500 garbage trucks run the test track every year on each way, which is equivalent to 149,000 single axle loads (80 kN ESALs) annually in the loaded direction or 4,265,000 ESALs over the pavements 20-year design life.

The RCA research project consists of four test sections of Jointed Plain Concrete Pavement (JPCP), totalling 180 metres in length and each consisting of 2 four metre wide lanes. The test sections were paved using concrete mixes utilizing RCA contents of 0% (control section), 15%, 30% and 50%.

The pavement structure consists of 250 mm of Portland cement concrete, 100 mm of asphalt stabilized open graded drainage layer (OGDL) and 450 mm of compacted granular material.

In JPCP pavements, transverse joint spacing is designed so that temperature and moisture stresses do not produce intermediate cracking between joints. The variable transverse joint spacing specified by the Ministry of Transportation of Ontario (MTO) was used. The MTO specified joint spacing follows a repeating pattern of 3.7 m, 4.5 m, 4.0 m and 4.3 m joints [11]. Epoxy coated dowel bars, 38 mm in diameter, were installed for load transfer at a 300 mm transverse spacing.

A view of the test track concrete sections is depicted in Figure 1. A single slab is highlighted in the image.

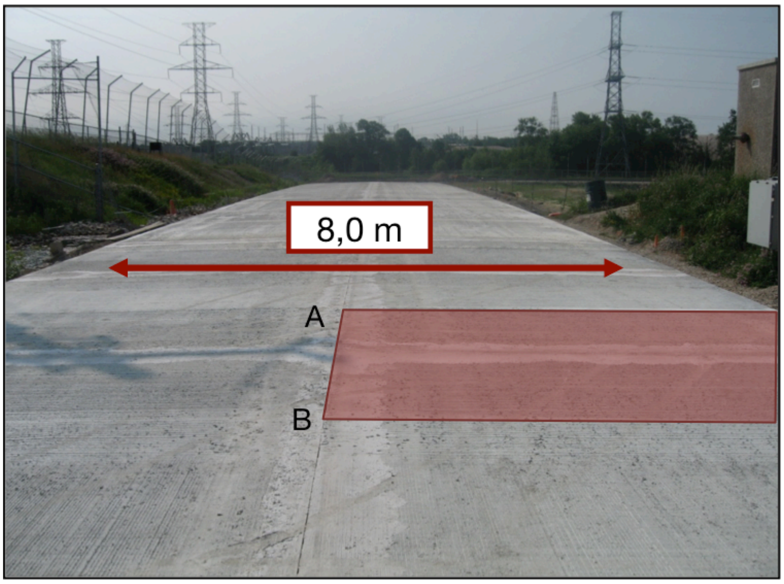


*Figure 1: View of the RCA concrete sections at the CPATT test track*

One slab in each of the four test sections was embedded with a variety of sensors. Each instrumented slab was embedded with 6 vibrating wire concrete embedment strain gauges, 2 vibrating wire vertical extensometers, 2 vibrating wire inter-panel extensometers and 2 concrete maturity meters.

Strain gauges were installed to measure the strains induced by vehicular and environmental loads in the long-term. Four out of six strain gauges are placed in the middle of the slab; two near the top of the slab and two near the bottom. At each location, one gauge was placed in a longitudinal orientation (parallel to the centreline of the road) and the other in a transverse orientation (perpendicular to the centreline of the road). The remaining two strain gauges are located at the edge of the slab, adjacent to a transverse joint: one at the top of the slab and the other at the bottom. The locations of the gauges were selected to provide a comprehensive picture of the structural behaviour of the slab by recording data from different positions.

Vertical and inter-panel extensometers were placed to measure the vertical and horizontal displacements of the slabs, respectively, due to thermal effects. One vertical extensometer and one inter-panel extensometer were installed at the edge of the slab at the centreline of the pavement. Another vertical extensometer and another inter-panel extensometer were located at the outer edge of the slab, next to the unpaved shoulders.

Maturity meters measure changes in the moisture content in the concrete slab, as it varies with time due to the aging of the concrete. The data from the maturity meters is not discussed in this paper.

Ambient temperature is measured by thermometers placed in the datalogger itself: it can be useful to assess the climate change and the possible time lag between ambient temperature and readings provided by all sensors.

The sensor placement in a single slab is portrayed in Figure 2 in a front view representation. The position of points A and B is the same as in Figure 1 and the line connecting the two points divides the represented slab from the adjacent one.

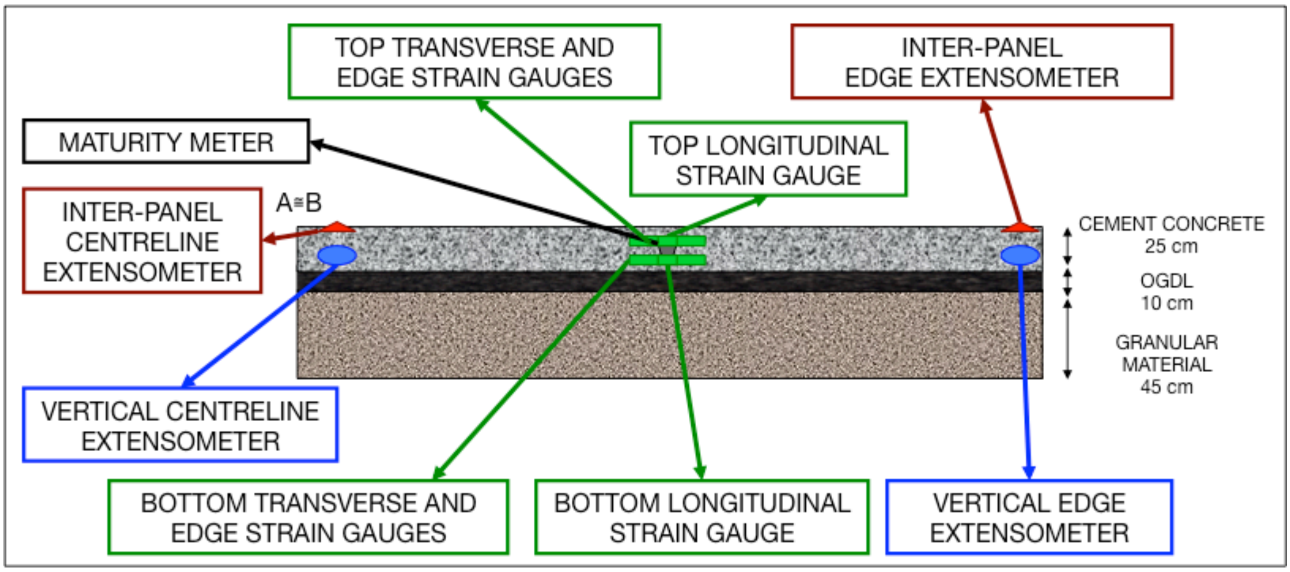

*Figure 2: Profile view of the sensor location in the pavement*

In Figure 3, the sensor locations are shown in a plan view. The line connecting the points A and B is located in the centreline of the roadway, consistent with the previous figures.

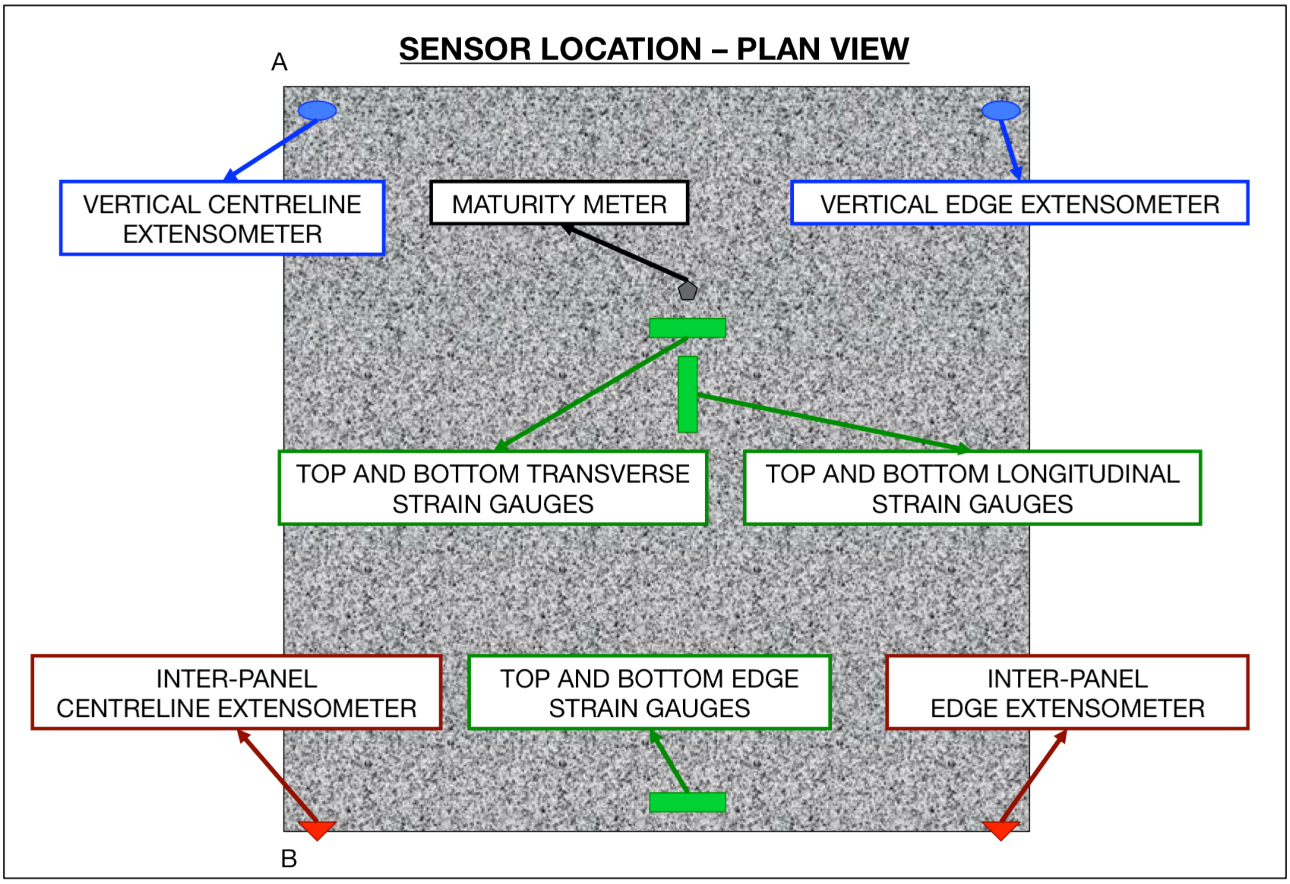


*Figure 3: Plan view of the sensor location in the pavement*

# 4. PERFORMANCE EVALUATION

## *4.1 SENSOR DATA ANALYSIS*

Continuous readings from the sensor began soon after construction was completed in 2007. A datalogger program has since been recording sensor measurements every two hours, so when the measurement is taken, a truck load may or may not be present; the effects of traffic on the pavement strains will not be discussed in this paper.

Data from 2007 to 2012 have been downloaded and analyzed. This data has provided valuable information about the behaviour of concrete slabs with respect to changing environmental conditions. Vibrating wire strain gauges can be particularly useful to evaluate the response of slabs to long-term environmental change, because they can show how strains are varying throughout the year, between the cold seasons and the warm seasons. At the same time, extensometers can provide useful information about the response of slabs in the short-term. In fact, by observing displacements, it is possible to assess how the shape of the concrete slab changes due to daily temperature variations.

### 4.1.1 STRAIN GAUGES

Strain gauges are sensors capable of measuring strains, expressed in parts per million or microstrains (με). Static strain gauges such as the ones installed on this project are best suited for measuring the strains induced by environmental changes, e.g. thermal effects, creep, moisture gradients.

Each strain gauge also measures the concrete temperature at the same time, as a thermistor is incorporated in the device. The concrete temperature can be compared to the ambient temperature and also correlated to the respective measured strain.

For this purpose, the data collected at the CPATT Test Track have been zeroed and corrected to take into account calibration factors, temperature variations and coefficients of thermal expansion, according to the following equation provided by the sensor supplier:

$$\mu\varepsilon_{(Calculated)} = \left(R_1 - R_0\right) \cdot \left(\frac{F}{F_0}\right) + \left(T_1 - T_0\right) \cdot \left(C_1 - C_2\right)$$

where:

$R_0$: mean strain reading;
$R_1$: single strain reading;
F: strain gauge calibration factor, equal to 3.405;
$F_0$: default strain gauge factor, equal to 4.062;
$T_1$: mean temperature reading [°C];
$T_0$: single temperature reading [°C];
$C_1$: coefficient of thermal expansion of gauge, equal to 12.2 με;
$C_2$: coefficient of thermal expansion of concrete, equal to 10.4 με [14].

Daily cycles in strain, concrete temperature and ambient temperature are observed in the data. During the day, the ambient temperature increases from the nightly low to the daily high, resulting in a corresponding increase in concrete temperature. The concrete is also influenced by heating, due to exposure to solar radiation. As the concrete temperature increases, the concrete pavement expands. This results in an increase in measured strains, i.e. greater tension. The opposite behaviour is observed overnight. After the sun sets and the air temperature cools, the concrete temperature also decreases and the concrete contracts, resulting in a decrease in strain, i.e. greater compression. The highest tensile strains are recorded during the warmest season and the greatest compressive strains are measured in the coldest season.

The peaks and valleys in the ambient temperature are slightly offset from the corresponding peaks and valleys in the concrete temperature and strains, since the concrete does not heat or cool as fast as the air. This phenomenon can be observed in Figure 4, where the ambient temperature, the concrete temperature and the calculated strains from the top longitudinal midslab strain gauge, placed in the 15% RCA section, from 2009 until 2012, are plotted. Similar trends are observed in the remaining sensors in the 15% RCA section, as well as all the strain gauges in the other sections (0%, 30% & 50% RCA).

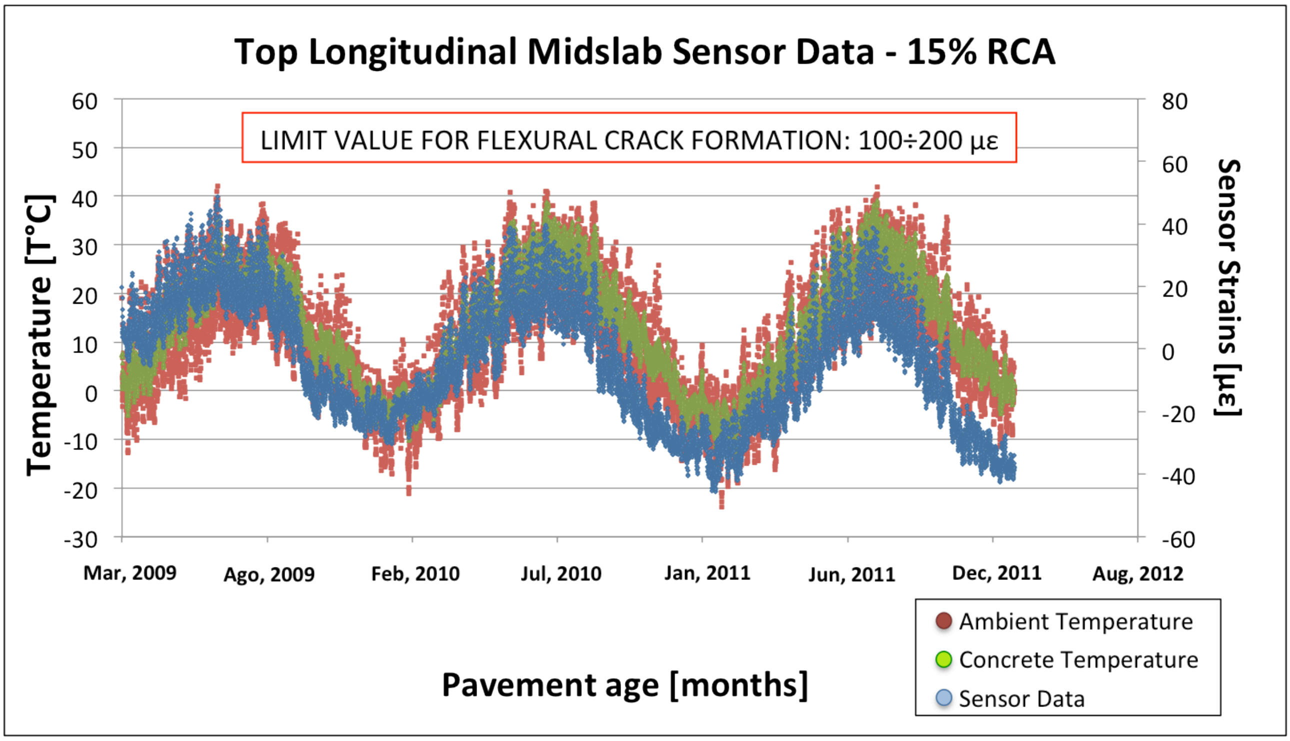


*Figure 4: Data of Top Longitudinal Midslab strain gauge, in the 15% RCA section*

In Table 1, the maximum recorded strain values in tension and in compression are reported year by year. As expected, the former occur in summer, when the temperatures reach the highest values and thermal expansion is greatest, whereas the latter occur in winter, when the temperatures are lower and thermal expansion is minimal.

*Table 1: Maximum and minimum strain values per year*

| | 2009 | | 2010 | | 2011 | |
|---|---|---|---|---|---|---|
| | Max. Tension | Max. Compression | Max. Tension | Max. Compression | Max. Tension | Max. Compression |
| Strain [με] | **48.7** | -28.0 | 39.6 | -40.4 | 38.6 | **-45.8** |
| Concrete Temperature [°C] | 33 | -3 | 37 | -8 | 35 | -11 |
| Ambient Temperature [°C] | 39 | -11 | 39 | -9 | 39 | -19 |
| Date | Jun, 24th 4:00 pm | Dec 10th 8:00 pm | Jul, 6th 4:00 pm | Dec 16th 10:00 am | Jul, 16th 4:00 pm | Jan 17th 8:00 pm |
| Δμε [με] | 76.7 | | 80.0 | | 84.4 | |
| $\Delta t_{CONC}$ [°C] | 35.6 | | 44.5 | | 45.6 | |
| $\Delta t_{AMB}$ [°C] | 49.7 | | 47.4 | | 57.7 | |

After five years, the maximum values in tension recorded is equal to 48.7 με, measured in 2009. This value is still far from the limit for flexural crack formation, traditionally considered to be between 100 and 200 με for a 30 MPa concrete [12]. Similarly, the limit in compression for crushing crack formation can be considered around

3500 με [12]. The measured value remain far from this limit, whose overall minimum value in compression is 45.8 με.

Statistical analysis has been carried out on strain data from each sensor to assess the existence of any correlation with concrete temperature.

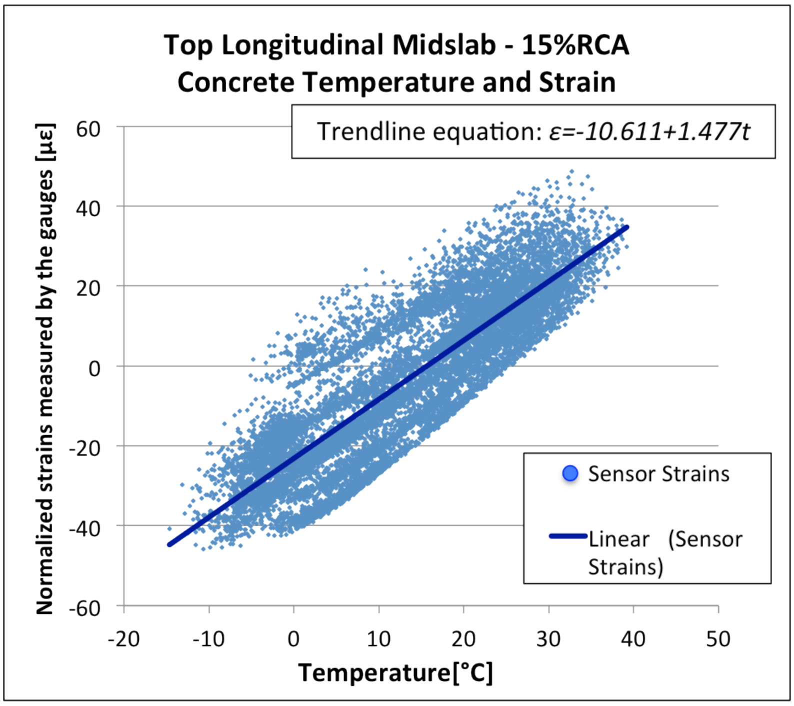


*Figure 5: Sensor strains and concrete temperature with a linear regression trendline*

Figure 5 depicts the data of sensor strains and concrete temperature, recorded by the Top Longitudinal Midslab sensor in the 15% RCA section. In the figure, the trendline, obtained by a linear regression model, is highlighted.

The basic statistics of the linear regression are reported in table 2. A clear relationship between strain and concrete temperature is observed. The former is directly proportional to the latter.

*Table 2: Linear regression statistics of Top Longitudinal Midslab – 15% RCA sensor data*

| **Linear Regression Statistics** | |
|---|---|
| *R* | 0.85 |
| $R^2$ | 0.72 |
| *Adjusted* $R^2$ | 0.72 |
| *Standard Error* | 10.34 |
| *Total Number of Cases* | 12,280 |

In comparing the results obtained by the corresponding sensor in different sections, similar trends are observed. Figure 6 shows details from a 9 month period. Different results in the top longitudinal midslab strain gauge are seen in the control section (0% RCA), the 15% RCA section and the 50% RCA section: in November, for instance, considering the 15% RCA section as a benchmark, the variation between 0% RCA and 15% RCA is around 30-40 με, almost twice as much the variation between 15% RCA and 50% RCA. Whereas the relative variation is significant, the range is short if compared to the limit values previously mentioned, attesting that the performance of the material is similar.

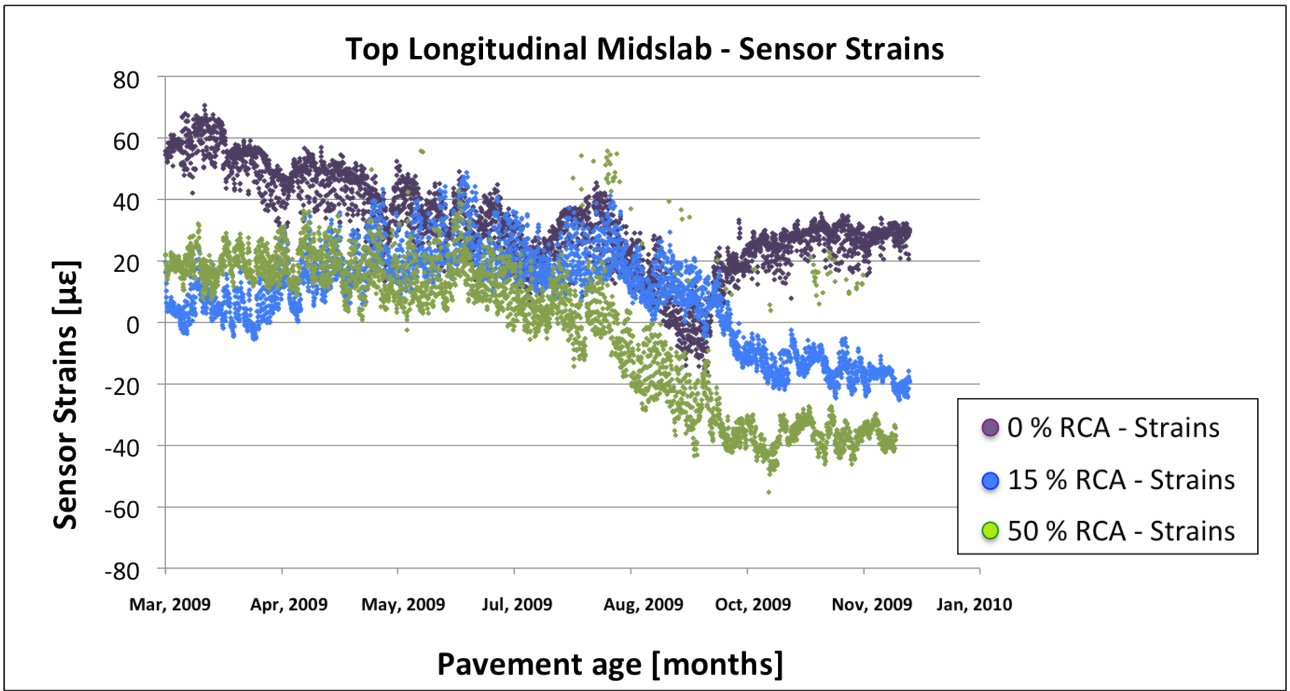


*Figure 6: Detail of 9 months concrete strains with different percentages of RCA*

### 4.1.2 VERTICAL EXTENSOMETERS

Vertical extensometers measure the vertical displacements of the slab edges. They can provide valuable information about changes in slab shape induced by temperature gradients, i.e. curling and warping. As previously mentioned, warm temperatures cause the concrete to expand, whereas cold temperatures cause concrete to contract. This phenomenon can be observed due to daily temperature variations. Daily temperature gradients, in fact, occur when one side of the slab is warmer or cooler than the other. During the day, the upper side of the slab is warmer than the bottom one, whereas during the night, this observation is reversed. The phenomenon is portrayed in Figure 7. During the day, the positive temperature differential creates a convex shape in the concrete slab, whereas during the night, the negative differential creates a concave shape.

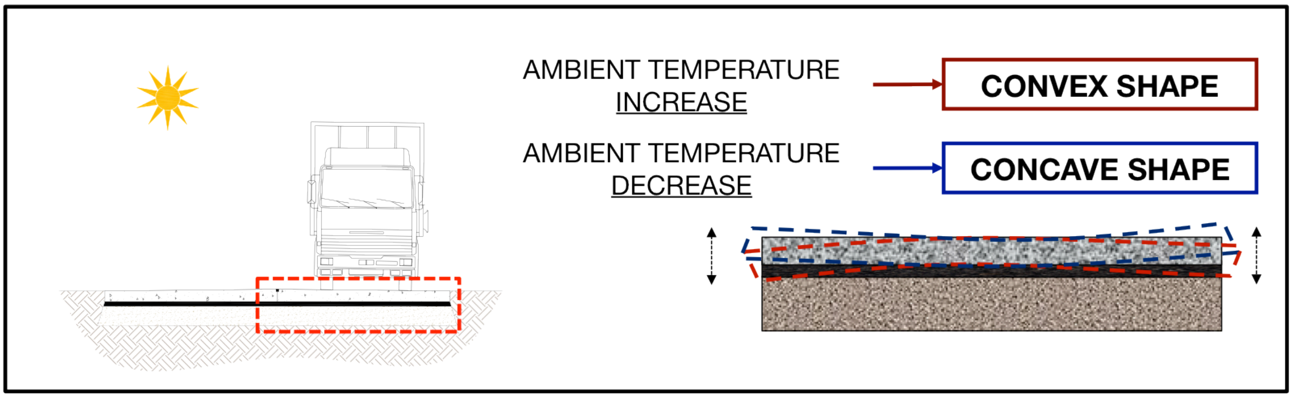


*Figure 7: Daily variations in concrete slab shape*

Recorded displacements confirm that slabs acquire a convex shape during the morning-afternoon and a concave shape during evening-overnight period. In fact, peaks in values mean that the edges, where sensors are located, are going downwards, whereas valleys mean that slab edges are going upwards, causing a concave shape. Results are consistent with the edge constraints, as each slab edges are not tied either to the adjacent slab or to the shoulders. In Figure 8, data are illustrated of the 15% RCA section over a four day period: highest values are measured in the late-afternoon hours, whereas lowest values are measured in the early morning hours.

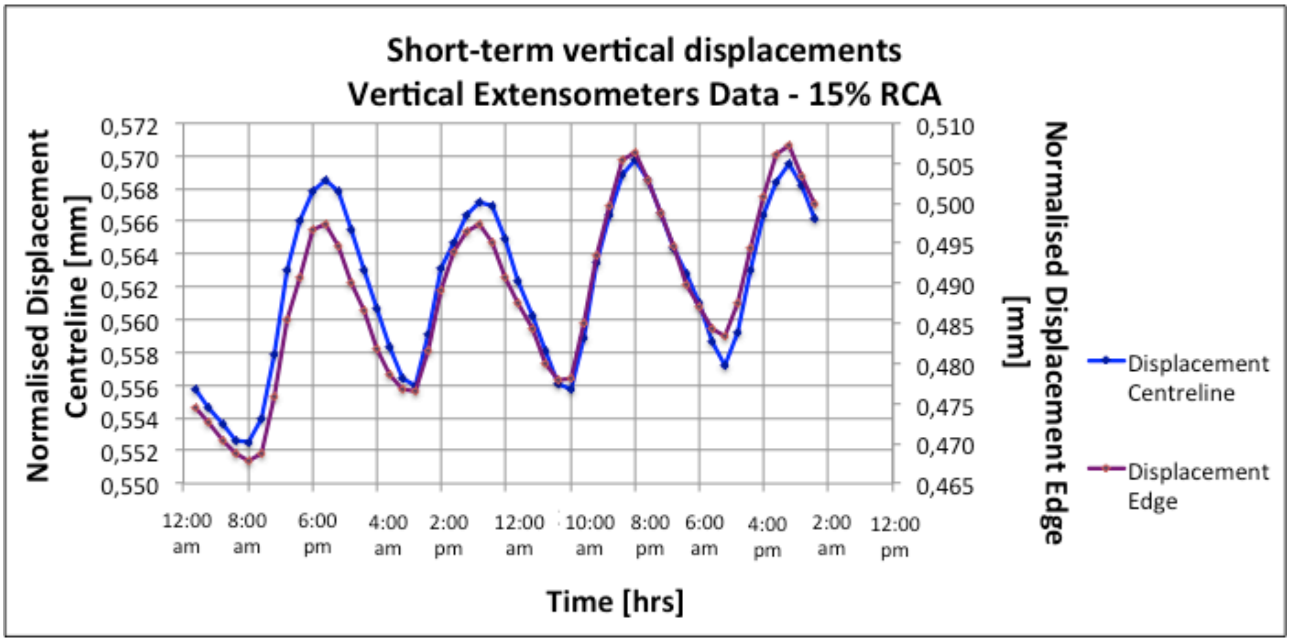


*Figure 8: Vertical centreline and edge displacements on a four-day period*

The image also shows that the displacement values are slightly different between the centreline sensor and the edge sensor: this can be due to the different boundary conditions, as the centreline sensor is adjacent to another slab, whereas the edge sensor is adjacent to the unpaved road shoulders. Somewhat greater variation is seen in the edge sensor data.

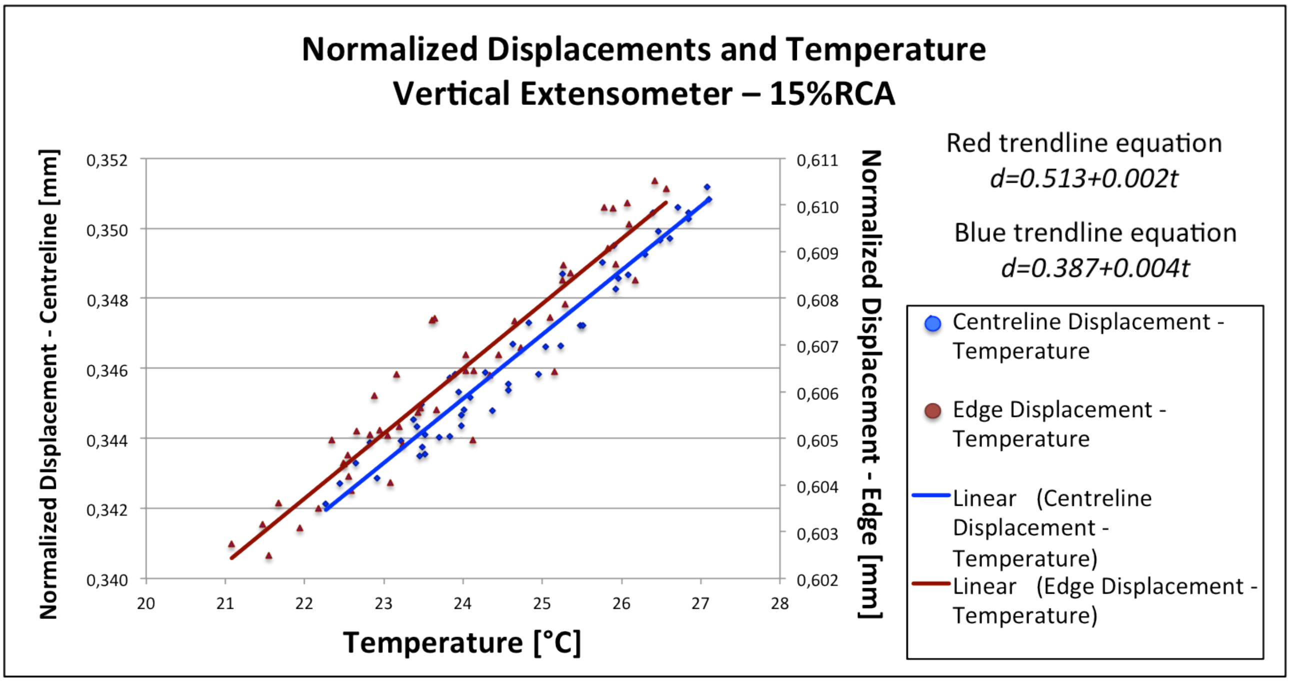


*Figure 9: Normalized displacements and temperature of the Vertical Extensometer*

The relationship between normalized displacements and temperature is depicted in Figure 9. The graph also shows the linear trendlines representing linear regression models for the four-day data reported in Figure 8.

The slope of both the linear regression trendlines is similar. This attests to the correlation between difference in normalized displacements and in temperature, in both the centreline and edge data. The basic statistics of the linear regression are summarized in Table 3.

*Table 3: Linear regression statistics of Vertical Extensometers – 15% RCA*

| Linear Regression Statistics - Vertical Extensometers | | |
|---|---|---|
| | CENTRELINE | EDGE |
| R | 0.97 | 0.99 |
| $R^2$ | 0.94 | 0.97 |
| Adjusted $R^2$ | 0.94 | 0.97 |
| Standard Error | 0.00 | 0.00 |
| Total Number of Cases | 49 | 49 |

Similar data trends are observed in the control section, as well as the 30% and 50% RCA sections. The data from the 15% RCA section has been reported in order to be consistent with the sensor data previously presented in this paper.

### 4.1.3 INTER-PANEL EXTENSOMETERS

Inter-panel extensometers measure the horizontal displacement that results from changing slab lengths due to the expansion and contraction of concrete. Changes in ambient temperature induce a corresponding change in concrete slab temperature, which causes the material to either expand or shrink. A positive variation occurs when the ambient temperature increases and it causes the concrete to expand, reducing the space between slabs at the joints. When the variation is negative, the process is reversed: concrete shrinks, increasing the space between slabs, as illustrated in Figure 9.

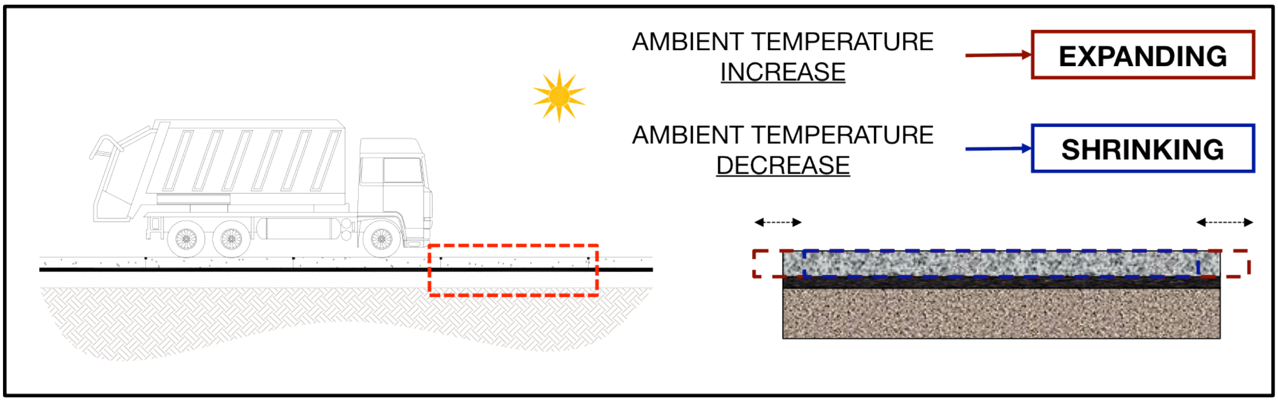


*Figure 10: Concrete expanding and shrinking due to ambient temperature variations*

The recorded measurements confirm that slabs expand during the morning and afternoon and contract during the evening and overnight. Peaks in inter-panel extensometer values indicate thermal expansion, i.e. the edges are moving outwards, whereas valleys corresponds to thermal contraction, i.e. slab edges are moving inwards, resulting in a reduced slab length. In Figure 10, data showing this behaviour has been plotted for the 15% RCA section over a four-day period.

The peaks and valleys in the inter-panel extensometer data also occur at the same time as the peaks and valleys in the vertical extensometer data, confirming the predicted behaviour of the material. Variations are uniform both at the centreline and at the edge of the slab. This behaviour is consistent with the type of edge constraints present, i.e. dowel bars uniformly spaced along the width of the slab.

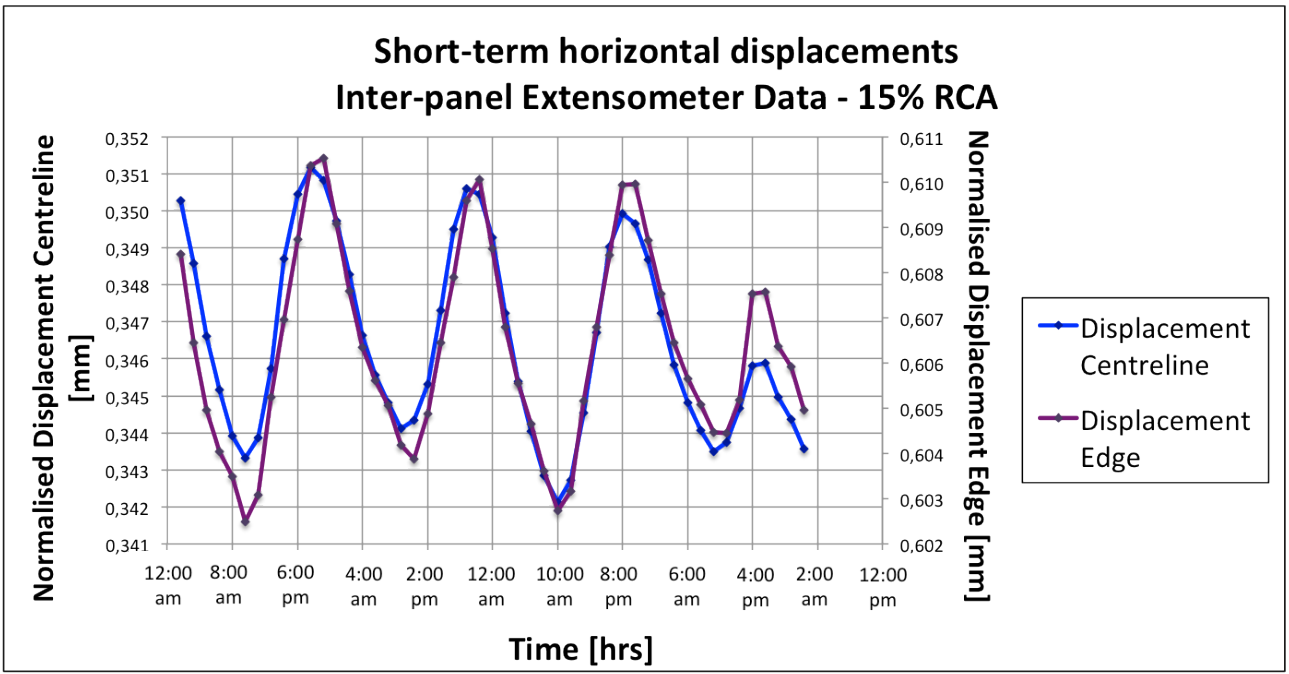


*Figure 11: Inter-panel centreline and edge displacements on a four-day period*

The relationship between normalized displacements and temperature is depicted in Figure 12. A linear regression model was also applied to the four day date reported in Figure 11. The linear trendline has also been plotted in Figure 12. Similarly to the vertical extensometer data, the slope of both linear regression trendlines is comparable. This indicates that that the ratio between variations in normalized displacements and in temperature is similar for both centreline and edge data.

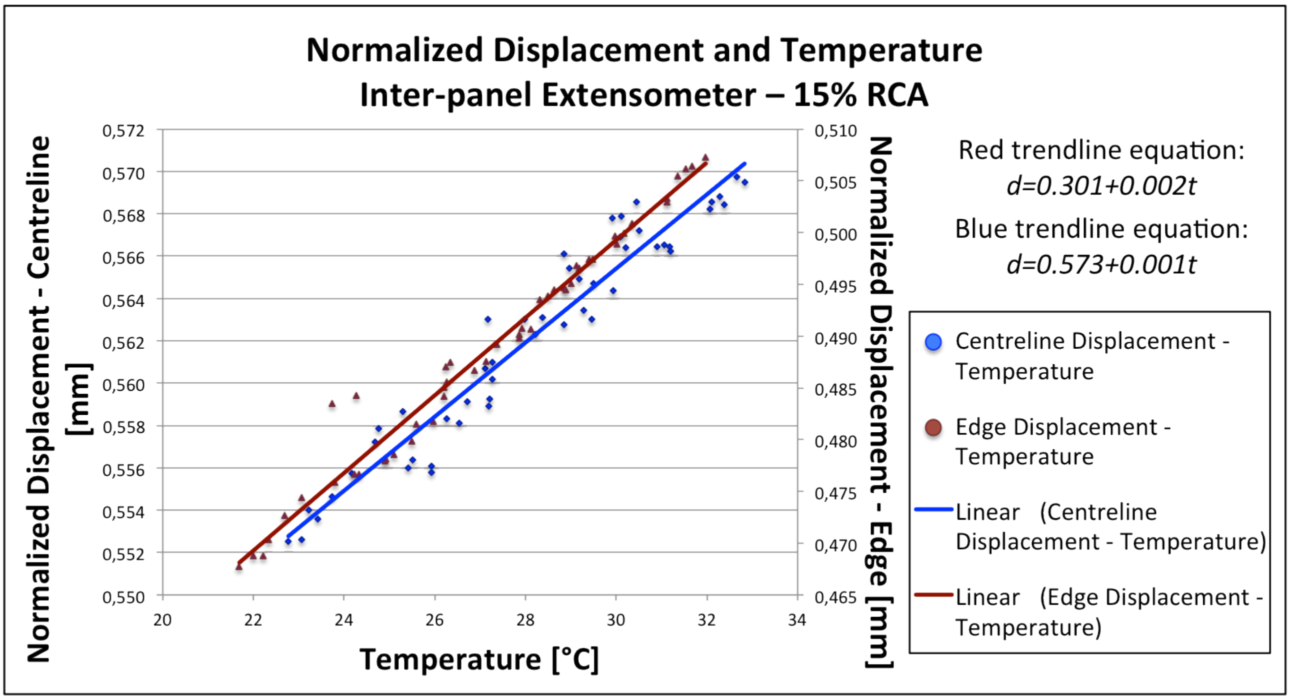


*Figure 12: Normalized displacements and temperature of the Inter-panel Extensometer*

The basic statistics of the linear regression are summarized in table 4. A high level of correlation between horizontal displacements and temperature is observed.

*Tab. 4: Linear regression statistics of Inter-panel Extensometers – 15% RCA*

| Linear Regression Statistics - Inter-panel Extensometers | | |
|---|---|---|
| | CENTRELINE | EDGE |
| R | 0.97 | 0.95 |
| $R^2$ | 0.95 | 0.90 |
| Adjusted $R^2$ | 0.95 | 0.90 |
| Standard Error | 0.00 | 0.00 |
| Total Number of Cases | 49 | 49 |

As with the strain gauge data and the vertical extensometer data, similar trends are observed for the control section (0% RCA), the 30% RCA section and the 50% RCA section. Again, data from 15% RCA section are reported in order to be consistent with the previous sensor data reported in this paper.

## *4.2 VISUAL EVALUATION*

After five years of service, all four test sections appear in very good condition. Only localized areas of minor distresses are observed. The pavement shows no evidence of structural damage. The most common distresses are the following:

- Intermittent, moderate ravelling, resulting in localized dislodgement of aggregate particles, which can be the consequence of traffic loadings or environmental effects, e.g. freeze-thaw cycles, allowing loosened pieces to be removed by traffic action;

- Surface abrasion and texture degradation, which can be caused by wear due to traffic action, concrete material properties, and construction quality;
- Occasional, moderate joint spalling, which is generally caused by a combination of traffic action, thermal expansion, and curling and warping;
- Few, slight corner cracks, usually related to the quality of joint construction and to concrete shrinkage [13].

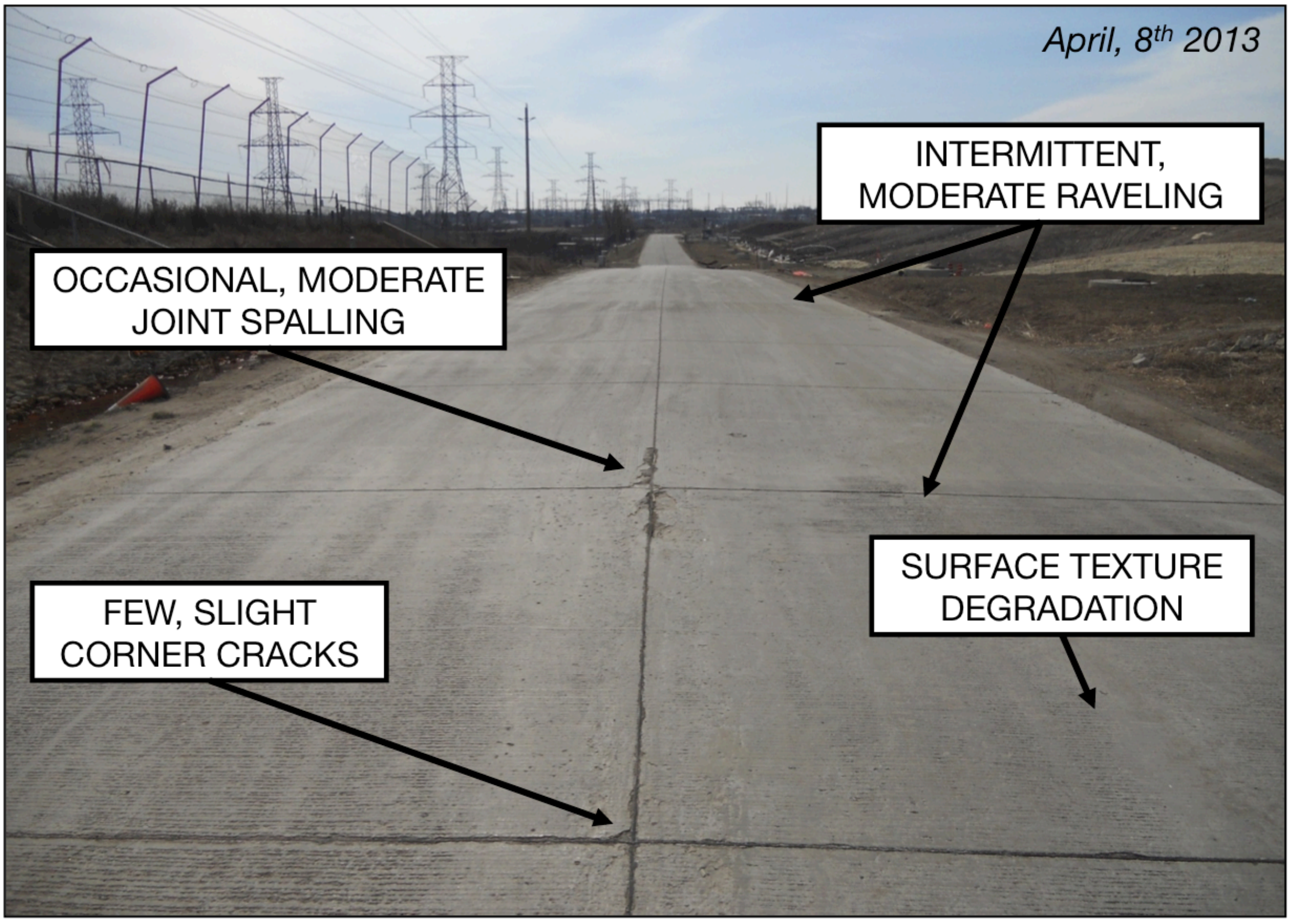


*Figure 13: View of the test track concrete sections and distresses*

The distresses observed are uniformly distributed across all sections, suggesting that RCA content has had a negligible impact on pavement performance so far.

Figure 13 depicts a recent picture of the rigid sections of the test track, where the most common distresses are highlighted. The photo shows that there is no evident sign of structural damage and that the distress distribution is uniform along the sections. The uniform distribution suggests that there is not a direct correlation between RCA content and the occurrence and distribution of surface distresses.

# 5. CONCLUSIONS

Four experimental concrete pavement sections, each containing a different percentage of RCA in the concrete mix, were built at the CPATT test track in 2007 and all remain in very good condition after being subjected to traffic loading for more than five years. These test sections were instrumented with a variety of sensors, which have provided valuable data for evaluating the long-term performance of RCA concrete in pavement applications.

After more than five years of service, comparable performance has been observed in all test sections, indicating that increasing RCA contents have not noticeably impacted the pavement performance. Sections only show minor distresses and no evidence of structural distress or damage have been observed. Furthermore, the distribution of the observed distresses is uniform throughout all RCA sections and the control section.

Statistical analysis has been carried out on strain gauge and extensometer data, confirming a good correlation between strains and temperature and between displacements and temperature.

Over the past five years, the highest flexural strains have been observed during the summer, whereas the highest compressive strains have been observed during the winter. The maximum and minimum values of vertical displacement occur at the same times as the maximum and minimum values in longitudinal displacement, confirming the relationship between changes in temperature and change in slab curvature, as well as the relationship between temperature and slab expansion and contraction.

Further testing will be carried out in the near future in order to evaluate the structural capacity, surface texture and frictional characteristics of each section at this stage in the pavement's lifecycle. More testing will also be performed in future years to continue assessing the performance of these road sections over a longer term.

The findings of this research suggest that the increased use of waste concrete in the form of RCA is feasible in concrete pavements, if performance comparable to virgin materials can be expected.

### *5.1 ACKNOWLEDGMENTS*

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