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Cement and Concrete Research 38 (2008) 538–542
Cement and Concrete Research

Identifying the effects of different construction practices on the spectral characteristics of concrete

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Received 23 May 2007; accepted 18 November 2007

Abstract

The objective of this study was to investigate the effects of different construction practices on the spectral characteristics of the concrete. Concrete blocks of identical shape and size ($20 \times 20 \times 6$ cm^3) were prepared using different treatment processes to establish eight different concrete characteristics. The different concrete treatments were: T_C (control), T_{NC} (no cure), T_{CL} (cool cure), T_H (heat cure), T_{HW} (high water content), T_{HC} (half cement), T_G (gravel), and T_L (limestone). Spectral reflectance of all the concrete blocks was obtained in the laboratory from 350–2500 nm spectral range using a portable, hand-held spectroradiometer. The spectral reflectance of the different concrete treatments varied systematically with changes in the concrete characteristics that resulted from different construction practices. Detailed spectral analysis shows that the spectral absorption features around 450, 1380 and 1850 nm are highly correlated with changes in the characteristics of the concrete. The spectral ratios R_{600}/R_{450}, R_{1380}/R_{1440}, R_{1850}/R_{1950} and R_{2150}/R_{880} can clearly differentiate the T_{NC}- and T_{CL}-treated concrete blocks from the other blocks with different concrete treatments. The spectral ratio R_{600}/R_{450} can differentiate the T_C-, T_G- and T_L-treatments, which were considered to have better concrete quality from the rest of the concrete treatments. The spectral results clearly indicate the potential application of spectral reflectance in assessing concrete characteristics after the concrete has hardened.

Keywords: Spectral reflectance; Concrete; Spectral ratios; Construction

1. Introduction

Monitoring and evaluating different concrete characteristics is one of the most important and costly problems involved in the construction process. Concrete is highly preferred in the construction of driveways, side walks, roads and buildings because of its high durability and low maintenance. The quality of new concrete construction depends on the composition of the mixed source materials, curing conditions, and quality of maintenance employed.

Mapping of concrete characteristics in different concrete surfaces such as driveways, side walks and roads has the potential for improving current practices in construction and maintenance of the infrastructure [1]. Recent advances in hyperspectral reflectance have shown that it is possible to derive the properties of different physical and chemical materials at a very detailed level from their spectral reflectances [2]. Spectral reflectance is a non-destructive, cost-effective approach for monitoring and mapping the spatial variability of concrete characteristics shortly after drying. Detailed spectral measurements involving large number of spectral bands with narrow bandwidths allow for precise identification of the chemical and physical properties of the concrete, as well as the surface geometry of the concrete surfaces [2,3].

Spectral reflectance of concrete surfaces has been studied previously to monitor aging of concrete sidewalks [3], to assess the degradation of concrete by chemicals, such as CO_2 [4] and to measure the solar reflectance of the concrete surfaces [5]. The new concrete sidewalks have higher spectral reflectance

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0008-8846/$ - see front matter
doi:10.1016/j.cemconres.2007.11.012

compared to the older sidewalks [3]. The decrease in spectral reflectance of older sidewalks was attributed to the accumulation of dust and dirt and to continued oxidation of concrete surfaces [3]. The spectral reflectance of normal concrete decreases as it is degraded by the action of CO_2 [4]. Aging and deterioration of concrete and asphalt road surfaces showed strong spectral evidence that these changes can be mapped using remote sensing [3,4,6]. However, none of the previous studies used spectral reflectance to map variations in concrete characteristics that arise as a result of different construction processes. Hence, the main purpose of this study is to provide a systematic and quantitative investigation of the unique spectral characteristics of concrete prepared under different construction practices.

2. Materials and methods

2.1. Construction of concrete blocks

A total of 32 concrete blocks of identical shape and size ($20 \times 20 \times 6$ cm^3) were prepared and subjected to eight different treatment processes. Each treatment had four replicates. The different treatments were: T_C (control), T_{NC} (no cure), T_{CL} (cool cure), T_H (heat cure), T_{HW} (high water content), T_{HC} (half cement), T_G (gravel used as coarse aggregate), and T_L (limestone used as fine aggregate). T_{NC}, T_{CL}, and T_H were three treatments that underwent different curing processes; T_{HW}, T_{HC}, T_G, and T_L were four treatments differing in their composition; and T_C was the control. Details of the different treatment processes are given in Table 1.

Each of the concrete blocks of the different treatments were made up of 2.72 kg of coarse aggregate, 2.49 kg of fine aggregate, 1.19 kg of Portland cement, and 0.3 L of water except for the T_{HC}-treated concrete blocks. Each of the T_{HC}-treated concrete blocks was prepared by using 0.62 kg of Portland cement. Hence, each of the T_{HC}-treated concrete block has 2.72 kg of coarse aggregate, 2.49 kg of fine aggregate, 0.62 kg of Portland cement and 0.3 L of water. The T_{HW}-treated concrete blocks were prepared with a high water–cement ratio of 0.8. The coarse aggregate used in the preparation of all the concrete treatments was limestone with a maximum size of 12.5 mm, except in T_G-treatments where it was gravel of size 12.5 mm. The fine aggregate that was used in all the treatments was natural concrete sand with a maximum size of 4.75 mm, except in the T_L-treatment, where it was fine aggregate of limestone with a maximum size of 4.75 mm. The concrete blocks of the T_C-, T_{HW}-, T_{HC}-, T_G-, and T_L-treatments were all cured at 21.1 °C for 21 days using wet burlap. The concrete blocks of T_{CL}-treatment were cured at 1.1 °C by covering them in ice and placing them in Styrofoam insulation. The samples of T_H-treatment were cured at 48.9 °C by placing them in an incubator, and the samples of T_{NC}-treatment were allowed to air dry at room temperature. All the concrete blocks of different treatments were prepared simultaneously.

Table 1
Composition and curing practices adopted in the preparation of different concrete treatments

Concrete treatment	Type of cure	Cure temperature	Duration of cure (# days)	Coarse aggregate	Fine aggregate
T_C	Control	21.1 °C	21	Limestone	Sand
T_{NC}	No Cure	21.1 °C	0	Limestone	Sand
T_{CL}	Cooler	1.1 °C	21	Limestone	Sand
T_H	Heat	48.9 °C	21	Limestone	Sand
T_{HW}	Control	21.1 °C	21	Limestone	Sand
T_{HC}	Control	21.1 °C	21	Limestone	Sand
T_G	Control	21.1 °C	21	Gravel	Sand
T_L	Control	21.1 °C	21	Limestone	Limestone

Fig. 1. Experimental set-up for collecting the surface spectral reflectance of concrete blocks.

2.2. Spectral reflectance of concrete blocks

A Fieldspec Pro spectroradiometer (ASD Inc., Boulder, CO) with a spectral range of 350–2500 nm was used to collect reflectance spectra of the concrete blocks in the laboratory, with a quartz–tungsten–halogen (QTH) lamp as a light source. Diffused light from the 100 W Lowell Pro-Light was used to illuminate the concrete block at 45° angles when spectra were collected in the laboratory. The fore-optics of the spectroradiometer were aligned vertically, and the height of the fore-optics from the top of the concrete block was adjusted so that reflected light only from the surface of the concrete block filled the field of view (FOV) of the instrument. The height of the fore-optics was kept constant throughout the experiment at 30 cm from the surface of each concrete block. The same experimental setup was used to collect the spectra of all the concrete blocks. The experimental setup for obtaining the spectral reflectance of the concrete blocks is shown in Fig. 1. Also spectra of the different ingredients that were used in the construction of the concrete blocks were obtained by pouring them into a Petri dish. The ingredients were: sand of size 4.75 mm, gravel of size 12.5 mm, limestone of sizes 4.75 and 12.5 mm, and Portland cement.

Calibration spectra of a white Spectralon panel (Labsphere Inc., North Sutton, NH) were acquired before recording the concrete spectra. The spectral recording software in the spectroradiometer was set in such a way that each reflectance spectrum recorded was obtained by collecting and averaging 20 individual reflectance spectra. Each spectrum was normalized by dividing with the measured spectrum of the standard (Spectralon panel). The configuration of ASD spectroradiometer consists of three detectors each collecting the spectra from 350–1050, 900–1850 and 1700–2500 nm spectral regions respectively. The spectra collected by these detectors within the instrument are not spliced together. Hence each normalized spectra was splice-corrected using the ASD View Spec software (ASD Inc., Boulder, CO). Individual spectral measurements of the concrete blocks of each treatment group ($n=4$) were then averaged to overcome individual spectrum variations. Spectral reflectances relative to the Spectralon standard were calculated from the averaged spectra ($n=4$) for each treatment group. Significant differences in spectral reflectance among treatments were evaluated through analysis of variance (ANOVA).

3. Results

The concrete blocks prepared from different treatments were all visually alike and are not distinguishable to the untrained eye. Fig. 2 shows the averaged ($n=4$) spectral reflectance of the concrete blocks from the eight different treatments applied in the laboratory. Because each of the four "individual" reflectance spectra were averaged over 20 spectra during data collection, the final averaged spectra shown in Fig. 2 are actually an average of 80 spectra of that particular treatment group. With in the visible part of the spectrum (from 400–700 nm), the concrete blocks shows reflectance minima (absorption maxima) in the ultra violet and blue wavelength regions near 350 nm and at 427 nm, respectively, and the reflectance gradually increases to a wavelength about 600 nm. There is a broad, shallow reflectance minimum between 600 and 1100 nm (centered about 850 nm), which is likely due to trace amounts of ferric iron present in the mixture. Except for two water absorption bands (reflectance minima) near 1400 and 1900 nm, the reflectance continues increasing in the near infrared (NIR) region from 1100 nm to about 1700 nm, then decreases from about 1700 nm to about 2500 nm.

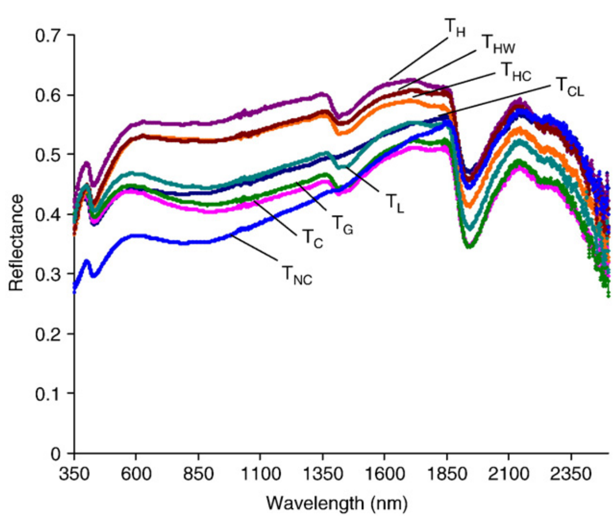

Fig. 2. Average surface spectral reflectance ($n=4$) of the concrete blocks from different concrete treatments. The different treatments were: T_C (control), T_{NC} (no cure), T_{CL} (cool cure), T_H (heat cure), T_{HW} (high water content), T_{HC} (half cement), T_G (gravel used as coarse aggregate), and T_L (limestone used as fine aggregate).

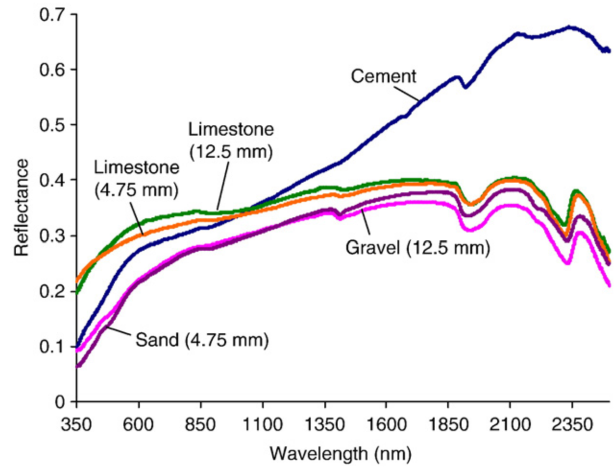

Fig. 3. Spectral reflectance of the different ingredients used in the construction of concrete blocks. The ingredients were: sand of size 4.75 mm, gravel of size 12.5 mm, limestone of sizes 4.75 and 12.5 mm and Portland cement.

Fig. 3 shows the reflectance properties of the different ingredients that were used in construction of the concrete blocks. Strong absorption bands associated with the molecular

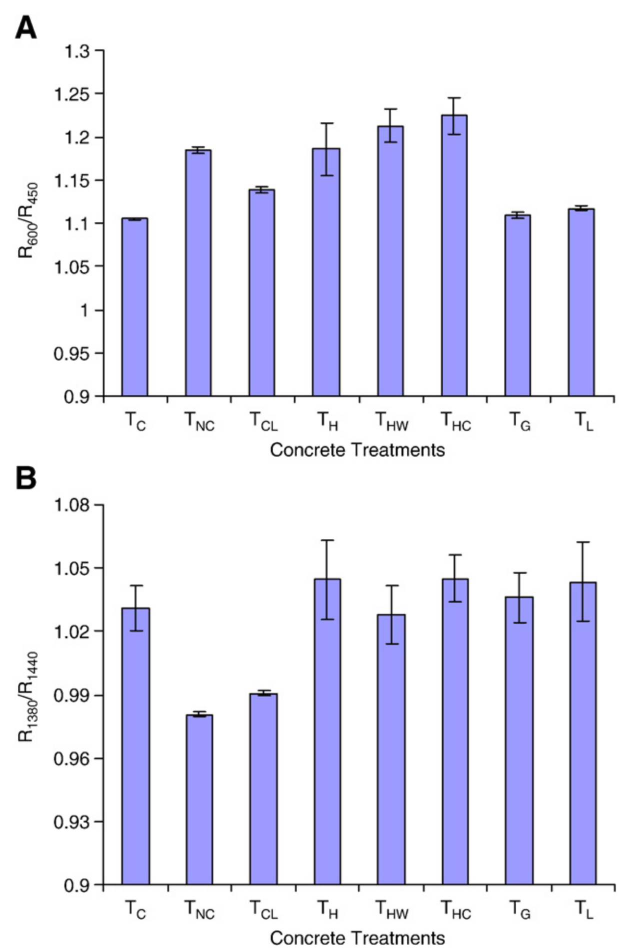

Fig. 4. Changes in R_{600}/R_{450} (A) and R_{1380}/R_{1440} (B) for different concrete treatments. Bars are ± one standard error from four replicates.

water and water of hydration were seen at 1400 and 1900 nm in the sand and gravel spectra and at 1900 nm in the spectra of the limestone and cement. The carbonates associated with limestone, sand and gravel also showed prominent absorption bands at 1900 and 2350 nm. The reflectance of the cement gradually increased throughout the spectral range from 350 to 2500 nm and remained significantly higher in the NIR region compared to the rest of the samples. The spectra of the concrete ingredients (Fig. 3) differ from the spectra of concrete blocks (Fig. 2) because each of these compounds undergoes hydration, followed by hardening to form the final concrete product.

The minor water absorption band extending from 1400 nm to 1500 nm is seen in spectral curves of all the concrete treatment blocks except in T_{NC}- and T_{CL}-treated concrete blocks. The major water absorption band extending from 1850 nm to 2150 nm is seen in the spectra of all the concrete treatments. But the depth of this major water absorption band is less for the T_{NC}- and T_{CL}-treated concrete blocks compared to the rest of the concrete treatments. In the visible region of the spectrum the increase in reflectance from 450 nm to about 600 nm region resulted in a gradual slope of the spectral curve. The intensity of this slope is low for the spectrum of the T_C-treated concrete blocks compared to other concrete treatments. A spectral ratio of 600 nm to 450 nm wavelength was calculated to mark the spectral difference in the intensity of slope. The values of the ratio index, R_{600}/R_{450}, was significantly ($p<0.05$) lower for the T_C-, T_G-, and T_L- treated concrete blocks, compared to the rest of the concrete treatments, as shown in Fig. 4A.

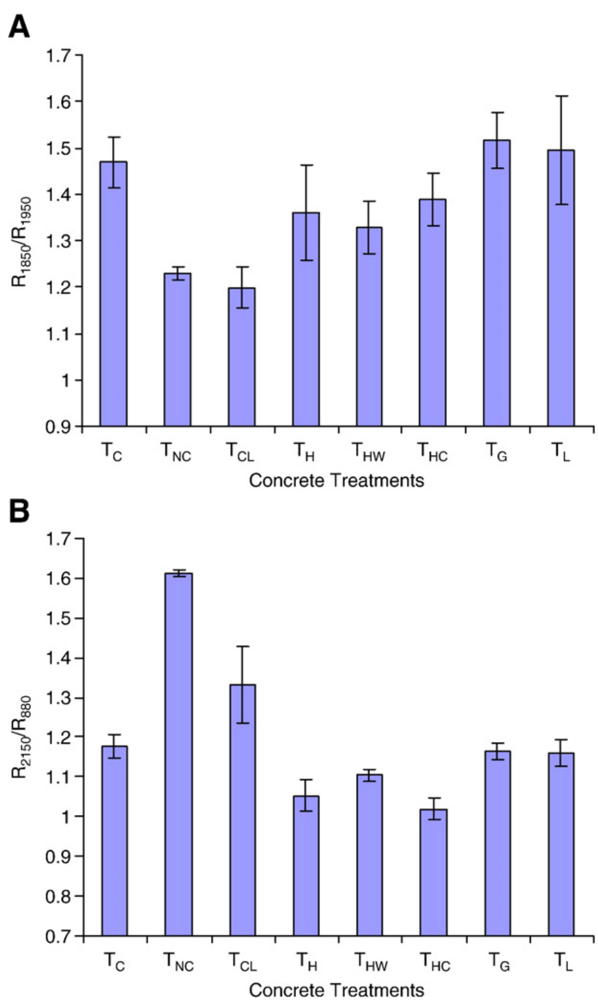

Fig. 5. Changes in R_{1850}/R_{1950} (A) and R_{2150}/R_{880} (B) for different concrete treatments. Bars are ± one standard error from four replicates.

The significant differences in the depth of minor water absorption bands of different treatments were calculated using a spectral ratio of 1380 nm to 1440 nm. As shown in Fig. 4B the values of this ratio index, R_{1380}/R_{1440}, were significantly ($p<0.05$) lower for the T_{NC}- and T_{CL}- treated concrete blocks compare to the rest of the treatments. Another ratio index, R_{1850}/R_{1950} was calculated to identify the differences in the depth of the major water absorption band in the different spectra of the concrete treatments. Only the T_{NC}- and T_{CL}-treated concrete blocks had lower R_{1850}/R_{1950} values and were found to be significantly different from the T_C-, T_G-, and T_L- treated concrete blocks (Fig. 5A). The spectral reflectance at 2150–2500 nm remains lower relative to the reflectance at 800–1300 nm region in the all the concrete treatments except in the T_{NC}- and T_{CL}-treated concrete blocks. A spectral ratio index of R_{2150}/R_{880}, based on this spectral feature, indicates that the T_{NC}- and T_{CL}-treated concrete blocks were significantly ($p<0.05$) different from the rest of the concrete treatments. As shown in Fig. 5B the values of the ratio index, R_{2150}/R_{880}, was significantly ($p<0.05$) higher for the T_{NC}- and T_{CL}-treatments and was significantly ($p<0.05$) lower for T_H, T_{HC}, and T_{HW}-treatments, compared to the rest of the concrete treatments.

4. Discussion

The spectral reflectance of the different concrete treatments varied systematically with changes in different concrete characteristics. Our in-depth spectral analysis shows that the spectral absorption features around 450, 1380 and 1850 nm change accordingly with changes in concrete characteristics (Fig. 2). On a different subject (chemical degradation of concrete) that did not use spectral ratios [4], the spectral reflectance of concrete around 440, 1393, 1930, 2127 and 2340 nm have high correlation with changes in concrete degradation over time due to CO_2, and thus with decline in concrete quality [4]. The spectral ratio indices, R_{600}/R_{450}, R_{1380}/R_{1440}, R_{1850}/R_{1950}, and R_{2150}/R_{880} that were identified in our study can differentiate the concrete treatments based on their production history, rather than their degradation with time.

The spectral change from the 450 nm absorption feature to the 600 nm reflectance peak in visible wavelengths clearly differentiates between the concrete blocks produced with different treatments (Fig. 2). The spectral ratio R_{600}/R_{450} (Fig. 4A) that was identified based on this spectral feature shows significant ($p<0.05$) decrease in the ratio for the T_C, T_G, and T_L-treated concrete blocks, compared to the rest of the concrete treatments. The T_{NC}, T_{CL}, and T_H-treatments, which were exposed to poor curing practices, and the T_{HW} and T_{HC}-treatments, which had high water content and only half the normal cement, respectively, of the regular concrete, are considered to have poor concrete characteristics, compared to the T_C, T_G, and T_L-treated concrete blocks. Hence, this spectral ratio can differentiate concrete with good characteristics from concrete that were treated with poor production procedures.

The hydration features common to all the concrete blocks occur at 1400–1500 nm and 1850–2150 nm in the NIR region of the spectra (Fig. 2). The T_{NC}- and T_{CL}-treated concrete blocks shows no hydration feature at 1400–1500 nm region and shows a decrease in depth of absorption feature at 1850–2150 nm region (Fig. 2). The spectral ratios, R_{1380}/R_{1440} (Fig. 4B) and R_{1850}/R_{1950} (Fig. 5A) that were based on these spectral features show that the T_{NC}- and T_{CL}-treatments were significantly ($p<0.05$) different from the rest of the concrete treatments. These differences in the water absorption features in the T_{NC}- and T_{CL}-treated concrete blocks can be attributed to the low molecular water inherent from these treatments. Poor curing practices applied in the T_{NC}- and T_{CL}-treated concrete blocks resulted in low water content and in concomitantly shallow absorption features in their spectra. Disappearance of the water absorption feature around 1450 nm as a result of concrete degradation by CO_2 was also reported [4]. The lower water absorption features in the T_{NC}- and T_{CL}-treatments also resulted in higher reflectance in the 2000–2500 nm compared to the 800–1300 nm spectral region. Thus, both of these treatments have significantly ($p<0.05$) higher values of R_{2150}/R_{880}, compared to the rest of the concrete treatments (Fig. 5B). The spectral ratios R_{1380}/R_{1440}, R_{1850}/R_{1950}, and R_{2150}/R_{880} can clearly differentiate the T_{NC}- and T_{CL}-treatments from the rest of the concrete treatments. The R_{1380}/R_{1440} and R_{2150}/R_{880} ratios can also differentiate the T_{NC}-treatment from the T_{CL}-treated concrete blocks. The application of the spectral ratios R_{1380}/R_{1440}, and R_{1850}/R_{1950} for aerial or satellite remote sensing studies is limited because of the presence of major atmospheric water absorption bands at about 1400 and 1900 nm respectively. However, these two spectral ratios are useful for hand-held, near-surface data collection, as in this case, because the atmospheric path is very short.

The results of this study clearly indicate the potential use of hyperspectral reflectance to map important concrete characteristics dependent on production practices. Spectral reflectances used alone display limitations in spectrally separating all the different concrete treatments from the control (T_C) treatment. However, the combination of different spectral ratios identified in this study clearly demonstrates that concrete treatments with better characteristics can be separated from the concrete treatments with poor properties. One limitation of this study is utilization of recently prepared concrete blocks with different production history for spectral investigation. It would be of interest to study how the spectra change over time in these concrete blocks, with variable rates of deterioration. Hyperspectral remote sensing, including the imaging of these spectral ratios, offers a new quantitative tool for the assessment of spatial variability of concrete characteristics caused by different production practices.

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