Analysis of Cement properties using Hyperspectral Remote Sensing methods

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Abstract

Understanding building material properties can play a key role in analyzing the health of structural elements in buildings. However, the field and laboratory tests can be laborious, time-consuming, and cost-intensive. Generally, the standard tests employed for characterizing the material properties are destructive in nature, but in the recent past, non-destructive testing (NDT) has given us the ease of understanding the material properties. Hyperspectral remote sensing technology has been exploited as one of the NDT methods for assessing the properties of building components. This study aims to investigate the quality information about cement using the hyperspectral remote sensing method and correlate it with the results of traditional quality testing methods. The materials used in the experiments included Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), and White Portland Cement (WPC). The cement samples were studied and experimented with for the identification of their types, and their temporal variability and changes in their spectral properties on which the strength of the samples depended were further checked. The study concluded that for OPC, PPC, and WPC, the absorption range is 1970 nm to 2020 nm, which is mainly due to the presence of different chemical compounds in cement. Also, the spectral reflectance decreases with time, and it can be concluded that in the present work, the strength of cement decreases with the decrease in spectral reflectance. Hence, Cement properties can be found using hyperspectral remote sensing data.

1. Introduction

Building materials are the essential components of any civil construction. Properties of the materials directly contribute to the quality of building structures. The quality of building materials is dynamically affected by numerous factors, including physical and chemical reactions on these materials, leading to a change in their originality(Ma et al., 2019**)**. Cement, a significant binder material in the construction industry, contributes significantly to the strength of structures(Singh et al., 2015). The quality of building materials is essential for efficient and sustainable structures. Various quality tests need to be conducted in the field and in laboratories. Destructive and non-destructive testing are the two common methods for evaluating the nature of these materials.

Non-destructive testing**(**Schabowicz**,** 2019) is a new approach to providing immediate results in near real-time for structures of any size. This method can be either field-based or laboratory-based and can be used flexibly.

Some of the few tests for cement quality estimation are chemical analysis, fineness, heat of hydration, compressive strength, and setting time. In a study **(**Olonade et al**.,** 2015**)** on comparative quality for the evaluation of cement brands, fineness, setting times, chemical composition, and compressive and flexural strength of different cement types are determined per BS and ASTM standards. A similar study is done in Bangladesh for the investigation of different cement brands and to check the cement's initial and final setting time, bulk unit weight, bleeding, normal consistency, fineness, and compressive strength at 3 days, 7 days, 14 days, and 28 days as per ASTM standards **(**Mohammed et al**.,** 2012**)**. Both studies provided information on different cement brands' chemical and mineral composition and the relation between various physical properties.

Another type of NDT method is Hyperspectral Remote Sensing (HyRS), which was developed in the 1980s and has excellent potential to identify different types of building materials **(**Ye et al**.,** 2015**)**. Hyperspectral sensors collect data in the range of 0.4 µm to 2.5 µm with a narrow bandwidth of 10 nm. Using larger bands means a contiguous spectral range and an abundance of spectral information may be available. HyRS data collection can be done through many sources, such as satellite-based sensors, unmanned aerial vehicles, field spectroradiometer, and hyperspectral imaging cameras. From all these, the method of data collection used in this study is a Spectroradiometer which is actually a ground-based data collection method(Paranjape, 2020).

In field spectroscopy, the principal goal is to use light to obtain an accurate measurement of the reflectance values of a surface and, from this, derive the physical properties of that surface. The reflectance properties of a surface are derived from the ratio of the incident light onto the surface to the light reflected from the surface.

A novel approach using hyperspectral airborne acquisition for identifying asbestos-cement (AC) roofs in urban areas has been developed to aid in assessing their degradation status. This method allows authorities to prioritize interventions effectively. Validation showed that some neighborhoods had up to 47% of their total area covered by AC roofs. Overall, Cartagena has over 9 km² of AC roofs. Two of the four methods tested successfully identified the condition of AC roofs on a large scale, demonstrating potential for wider urban application in public and environmental health planning(Enrique valdelamar martínez et al., 2024).

One of the important techniques of HyRS is spectral analysis, which studies the spectral characteristics of absorption valleys and reflection peaks. Spectral characteristics are related to the physical and chemical properties of the target object, which is important for the analysis (Herold et al., 2004). The spectral reflectance signature is the variation of reflectance at different wavelengths. Different materials have different transmittance, absorption, and reflectance in different wavelengths. Targets can be identified and classified by their spectral reflectance signatures. Hence, remote sensing is considered a non-destructive method to test for quality assessment, as the materials' spectral characteristics are directly related to the engineering properties of the construction materials. So many studies have been done on the analysis of material using hyperspectral Remote sensing. However, the range for which they were considered was up to 900 nm only, and the major changes in building material were seen in the range from 1400 nm to 2500 nm.

This study aims to investigate the quality information about cement using the hyperspectral remote sensing method, and the materials used in the experiments included ordinary Portland cement (OPC), portland pozzolana cement (PPC), and white Portland cement (WPC). Data collection is done through a ground-based sensor called a spectroradiometer, and finally, a correlation is built between the properties of cement and its spectral signature.

2. Data and Experiment methods

2.1 Cement Samples

The cement samples are shown in Figure 1, and the chemical composition of OPC, PPC, and WPC conforming to IS:8112, IS:1489-part-I, and IS:8042, respectively, which are used for analysis and are given in Table 1. The chemical components used in the study are Silica (SiO_2), Alumina (Al_2O_3), Iron Oxide (Fe_2O_3), Calcium Oxide(CaO), Magnesium Oxide (MgO) and Sulphur Trioxide (SO_3).

Figure 1. Sample of Ordinary portland cement(OPC), Portland pozzolana cement(PPC) and White portland cement(PPC)

Table 1. Chemical composition of different types of cement

Chemical Components	Weight (%)		
	OPC	**PPC**	**WPC**
SiO_2	20-21	28-32	21-25
Al_2O_3	5.2-5.6	7-10	0.86-0.92
Fe_2O_3	4.4-4.8	4.9-6	0.26-0.30
CaO	62-63	41-43	60-69
MgO	0.5-0.7	1-2	1.5-1.9
SO_3	2.4-2.8	2.4-2.8	2.9-3.3

2.2 Spectral Data Collection Experiments

The spectroradiometer instrument (svc hr-1024i), as shown in Figure 2, having a range of (350 nm-2500 nm) uses 3 diffraction grating spectrometers with 1 silicon and 2 Ingaas diode arrays. The silicon array has 512 discrete detectors, and the Ingaas arrays each have 256 discrete detectors that enable the reading of 1024 spectral bands.

Instrument was set as per the experimental requirement and calibrated by taking reflectance measurements of a reference (white plate), which is used to compute the ratio of the target scan to that of the reference. The data collection is conducted in a controlled environment within a black room setup, which is specifically designed for the experiment to minimize external light interference and ensure that spectral signatures can be obtained accurately. This controlled setting helps to eliminate stray light and maintain consistent conditions, thereby enhancing the reliability and precision of the collected data.

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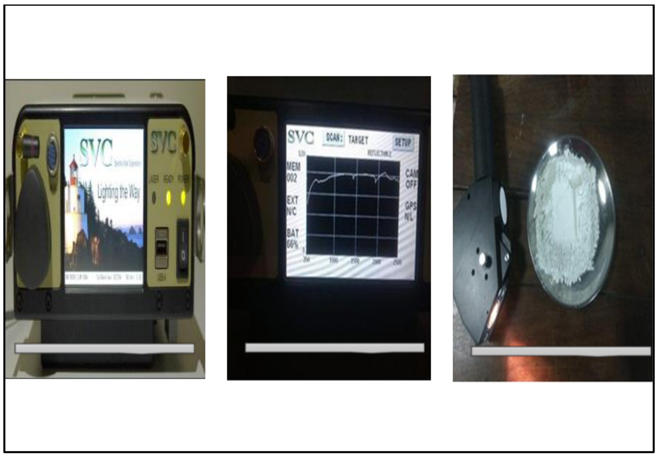

Figure 2. Instrument used for the collection of data samples

The spectral readings of the three cement samples were measured by the spectroradiometer. Ten readings each for three known and two unknown samples were recorded and stored in the instrument in sig file format. The readings were used to check the spectral similarity and dissimilarity between the known and unknown cement samples, followed by analyzing the effect of atmosphere exposure on cement for six months (1-month interval basis) using spectral classification methods as the binding property and strength of cement depends upon its capacity for chemical reaction, which takes place in the presence of water. Cement, if not stored properly, can absorb moisture from the atmospheric air and can react chemically. Two methods that were used for the analysis are the spectral angle mapper (SAM) and spectral information divergence (SID).

SAM is a spectral classification method measuring the angular similarity between a pixel's spectral signature and a reference signature in hyperspectral imagery, while SID (Chein-i chang, 1999) is a metric in remote sensing, gauging the difference between spectral vectors by assessing the angular deviation, indicating spectral dissimilarity.

Equation 1 was used in SAM, while Equation 2 was used in SID.

$$\boldsymbol{SAM(A,B) == cos^{-1}\left(\frac{\sum_{i=1}^{n} A_i B_i}{\sqrt{\sum_{i=1}^{n} A_i A_i \sqrt{\sum_{i=1}^{n} B_i B_i}}}\right)} \quad (1)$$

$$\boldsymbol{SID(A,B) = \sum_{i=1}^{l} A_i \log(\frac{A_i}{B_i}) + \sum_{i=1}^{l} B_i \log\left(\frac{B_i}{A_i}\right)} \quad (2)$$

Where

A is the actual spectral vector,
B is the estimated spectral vector,
and *n* is the number of bands.

3. Results and Discussions

3.1. Spectral Classification of Cement

The spectra of Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC) and White Portland Cement (WPC)were noted prior to taking the data of spectra of two unknown cement samples. The average spectral reflectance curve for OPC, PPC and WPC were calculated and plotted as shown in figure 3, and with unknown samples in figure 4.

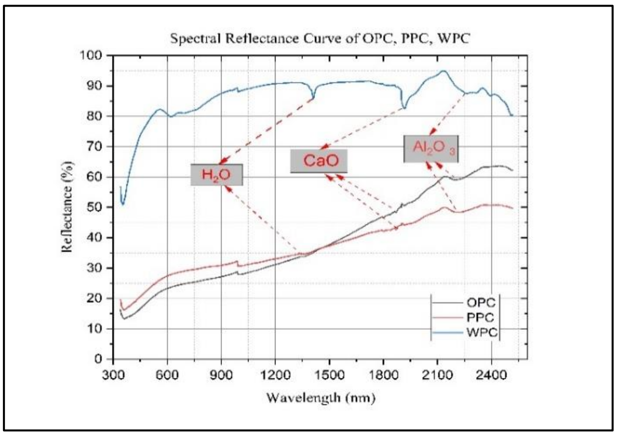

Figure 3. Spectral Reflectance Curve of Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC) and White Portland Cement (WPC)

The spectral reflectance of cement depends on its chemical composition, surface roughness, particle size and shape, mineralogy and crystal structure, and temperature. It is seen in Figure 3 that WPC reflectance is very high as compared to OPC and PPC. The absorption shown at the 1450 range is due to the presence of small moisture, which is available in cement and at 2000 nm range is due to the presence of CaO, and absorption at 2200 nm range is due to the presence of AL_2O_3.

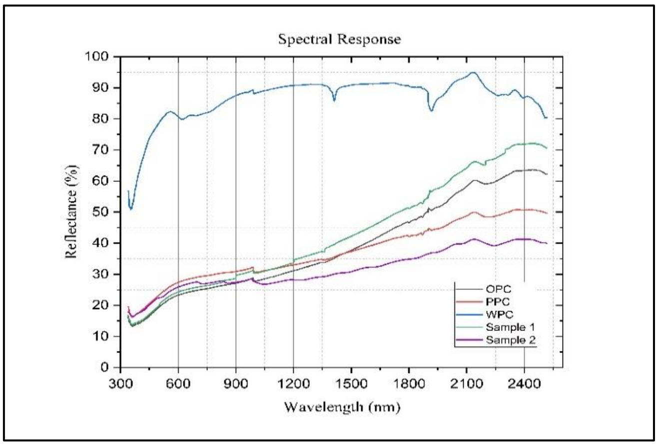

Figure 4. Spectral Reflectance Curve of Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), White Portland Cement (WPC), Sample 1 and Sample 2.

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In the above graphs it is clearly visible that the spectral data of OPC, PPC and WPC were considered as references to which the spectra of unknown samples were measured as shown is Figure 4. Table 2 show a comparison between each pair of cement samples**.**

Table 2. Spectral Angle (radians) using SAM classification method

REFERENCE SIGNATURES		**OPC**	**PPC**	**WPC**
Unknown sample	Sample 1	0.0324	0.1474	0.4251
	Sample 2	0.2424	0.0903	0.2011

SAM classification (Table 3) showed the least spectral angle, 0.0324, for sample 1 and OPC and 0.0903 for sample 2 and PPC.

Table 3. Spectral divergence using SID classification method

REFERENCE SIGNATURES		**OPC**	**PPC**	**WPC**
Unknown sample	Sample 1	0.0019	0.0224	0.1842
	Sample 2	0.0670	0.0094	0.0397

SID classification showed the least spectral divergence, 0.0019 for sample 1 and OPC and 0.0094 for sample 2 and PPC. Validation can be done through visual interpretation of graphs. From the results derived from the experiment, it can be concluded that sample 1 is Ordinary Portland Cement (OPC), and sample 2 is Portland Pozzolana Cement (PPC)

The above results show a significant spectral correlation between the building materials and similar chemical compositions, which can be distinguished using HyRS. Cement-type identification with the naked eye can be unruly and misleading. Laboratory tests can be time-consuming, and field tests are conducted in the absence of laboratory tests, which give approximate estimations.

The remote sensing technique provides an alternative solution to identify the different types of cement using spectral information on the chemical composition of different types of cement.

3.2 Study on the temporal variations of cement properties

Figures 5, 6 and 7 show the trend of the surface reflectance of OPC, PPC and WPC, respectively, the samples of which were kept open for a period of 6 months from November 2022 to April 2023, as shown in these Figures. Cement, when left exposed to the atmosphere, absorbs moisture, thus increasing its water content and resulting in a lower spectral reflectance.

The spectral reflectance of all three types of samples varies (OPC/PPC/WPC (Nov>Dec>Jan>Feb>Mar>Apr)).

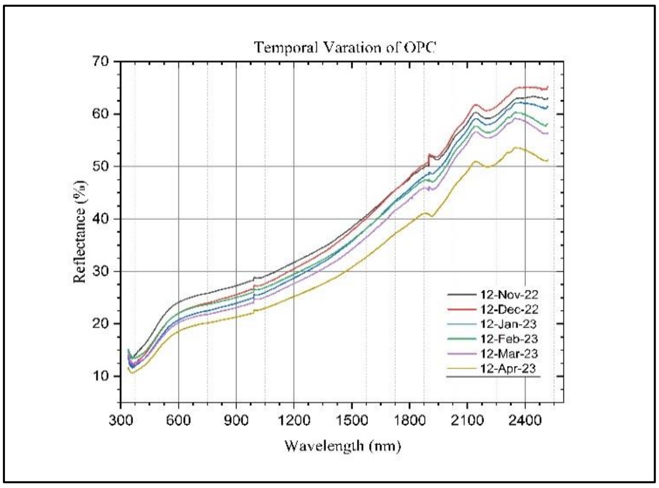

Figure 5. Temporal Spectral Response of Ordinary Portland Cement (OPC)

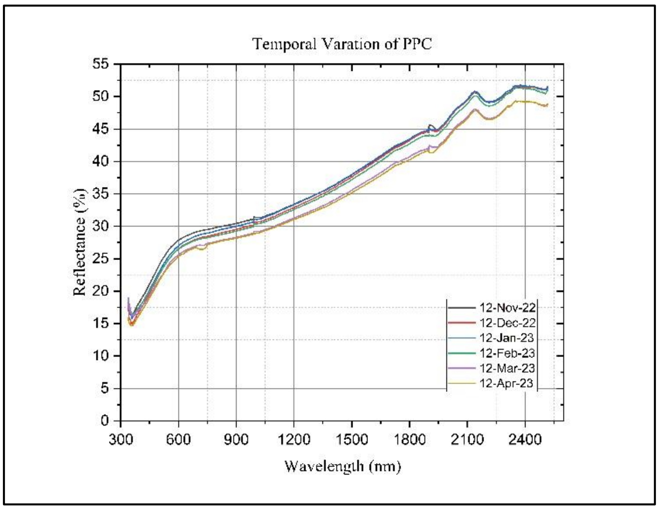

Figure 6. Temporal Spectral Response of Portland Pozzolana Cement (PPC)

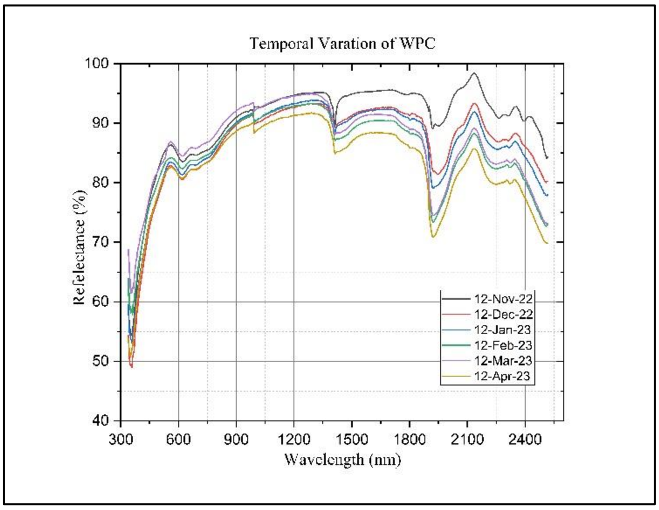

Figure 7. Temporal Spectral Response of White Portland Cement (WPC)

The binding property and strength of cement depend upon its capacity for chemical reaction, which takes place in the presence of water. Cement, if not stored properly, can absorb moisture from the atmosphere air and can react with it chemically**.** The variability of the spectral response of ordinary Portland cement and white Portland cement is very distinct and prominently visible. Due to water absorption from the atmosphere, the reflectance of cement decreased with time. The water molecules absorption for white Portland cement lies in the wavelength range of 1750 nm to 2100 nm, and a sudden dip in the spectral reflectance curve is distinctly visible. The spectral reflectance of Portland pozzolana cement has been less affected by atmospheric moisture and shows fewer spectral variations. This may be due to pozzolana Portland cement's lower water absorption than ordinary Portland cement, which can be attributed to the impermeability nature of the pore structure refinement in pozzolana Portland cement.

The secondary hydration reaction reduces the hydrated lime content in PPC cement types. The formation of calcium hydroxide and calcium silicate hydrate causes the growth of calcium silicate hydrate crystals, which become thicker and make it difficult for water molecules to reach the un-hydrated cement compound. In short, cement tends to absorb atmospheric moisture, causing hydration, hardening, and lumping of cement, which leads to cement's low strength development.

Analyzing the cement behavior by taking spectral measurements at different time intervals showed that the effect of atmospheric moisture on cement can be observed in terms of spectral reflectance, and changes in the quality of cement can be detected using a remote sensing-based method.

4. Conclusion

In the present study, cement samples were studied. They experimented with the identification of their types on the basis of their spectral properties. They were further checked for their temporal variability and changes in their spectral properties on which the strength of the samples depends. The study concluded that for OPC, PPC and WPC, the absorption range is 1970 nm to 2020 nm, which is majorly due to the presence of CaO, and the values near 2200 nm are due to the presence of Al_2O_3.

From the standard samples, properties of unknown samples were identified using numerical methods *viz.* SAM and SID. The other part of the study included the exposure of cement to an open atmosphere for a duration of 6 months, and it was found that all three types of cement samples absorb moisture in the range of 1750 nm to 2100 nm. A sudden dip in the spectral reflectance curve is distinctly visible for all three samples, but it was further ascertained that the dip for the sample WPC was more in comparison to OPC and PPC owing to more water absorption by it. Also, the spectral reflectance decreases with time, and it can be concluded that in the present work, the strength of cement decreases with the decrease in spectral reflectance.

The remote sensing method relates the spectral properties with the many engineering properties of materials. Although this material testing method is easy, efficient, and convenient, the spectral information alone is insufficient and requires validation through conventional tests/reference dataIn this research, only a few properties of cement have been studied, which can be extended for greater understanding and study of other properties of cement using hyperspectral remote sensing.

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