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Optical emission spectroscopy for concrete strength evaluation utilizing calcium lines

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ABSTRACT

Concrete is one of the most important materials in construction engineering. Evaluation of in-Situ concrete strength has become of great concern in construction process as well as for quality control. There are many destructive tests which can be conduct for the strength evaluation and for other performance parameters as well. However, load tests or core tests are not always possible or practicable. Since last decade, non-destructive testing has been widely accepted throughout the world in order to assess the quality of in-situ concrete. Compressive strength is considered as the most common measurement used by engineerings in design. The results of this test indicate if the concrete fulfills the requirements of the desired structure or not.

In the present work, the laser-induced breakdown spectroscopy (LIBS) technique has been used as a diagnostic tool for the elemental composition of concrete and determination of the compressive strength. The ratio between the ionic calcium lines at 393.3 and 396.8 nm and the neutral line at 422.6 nm have been utilized to measure their compressive strength. These lines are reversible lines, as they are greatly self-absorbed. The self-absorption of calcium lines under investigation was corrected via comparison of the electron densities. These densities have been measured from calcium lines to that computed from the hydrogen Hα-line at 656.27 nm which are in the same spectra under the same state. A linear relationship has been obtained between compressive strength and the ratio of the calcium ionic to atomic spectral lines intensities (Ca II/Ca I). The results showed an acceptable with high accuracy linear relations.

A new relation has been developed for comparison between compressive strength and the plasma temperature. The results reflect the importance of correcting the intensity of the emitted spectral line for the self-absorption effect before utilizing the compressive strength measurement in LIBS experiments. Also, it has been confirmed that the LIBS technique can be considered as a trustful semi nondestructive concrete strength test.

1. Introduction

Concrete is one of the essential products of infrastructure buildings. It is composed of heterogeneous materials. Cement is one of the primary components of concrete besides fine/coarse aggregates of sand, water, and stone with different mixing ratios [1]. Building capacity evaluation requires the expectation of seismic performance, restoration purposes, after some incomplete structural damages [2]. The concrete structure has a crack formation under specific loads which leads to increase the maintenance cost and limits durability [3]. Non-destructive testing can be applied to both old and new structures. For new structures, the principal applications are likely to be of quality control or the resolution of doubts about the quality of materials or construction. The testing of existing structures is usually related to an assessment of structural integrity or adequacy. In either case, if destructive testing alone is used, for instance, by removing cores for compression testing, the cost of coring and testing may only allow a relatively small number of tests to be carried out on a large structure which may be misleading. Non-destructive testing can be used in those situations as a preliminary to subsequent coring. The mixing ratio of its components is a significant factor in determining its characteristics such as compressive strength. Its industries are frequently searching for a micro-filler with a relatively little cost, which improves the real properties like compressive strength, permeability, and durability. Moreover, other characteristics of concrete, such as elastic modulus, water stiffness, and resistance to weathering

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agents including aggressive waters, are directly related to strength and can, therefore, be concluded from its data. So, compressive strength is a fundamental characteristic of concrete [1]. Several traditional methods have been conducted to measure the compressive strength of concrete. Coring, manual test hammer, digital test hammer, the Windsor pin and the Windsor probe are among these methods. They differ from each other in the compressive strength range, coefficient of variation and in the cost [4].

The LIBS technique is used to determine the compressive strength of concrete samples. It is a quick, semi nondestructive, remote and straightforward method. Also, it is utilized for elemental analysis of the concrete. It is a technique in which matter (solid, liquid or gas) is excited to a plasma state by using high-power lasers [5]. The spectral emission of the plasma is affected by the concentration of the element in the sample and the plasma features, which in turn depends on the excitation source properties, the ambient gas, plasma initiation and expansion process. Two main parameters of the plasma are the electron density and electron temperature. They must be measured to accomplish a sensitive quantitative analysis [6,7]. In the passive optical emission spectroscopy mode, light analyzers (spectrographs) with a graphical readout are employed to give the characteristic spectrum. A spectrum is a relation between the output emission intensity and the emission wavelength [8–10]. It was proved that the ratio between the ionic and neutral spectral line intensities is related to the compressive strength of irradiated target [11]. It was also stated that the plasma temperature is directly proportional to the surface compressive strength [12]. The calculation of plasma temperature depends on the intensity of the spectral line. The measurement of a precise spectral intensity needs a line which is free from self-absorption effect [13,14]. Self-absorption effect takes place in general in any radiation emitted system, such as plasma [15]. Theoretically, it affects the lines emitted from the primary element in the target material in LIBS experiments. The calcium lines are of the interest in concrete plasma where the calcium part is one of the principal constituents in actual samples. So, the calcium neutral line at 422.6 nm and ionic lines at 393.3 nm and 396.8 nm are utilized to measure its compressive strength. However, these lines are resonance lines and may be subjected to self-absorption effect. It is well known that this effect reduces the line intensity and increases its full width at half maximum (FWHM). In this investigation, the compressive strength of concrete has been calculated and the electron temperature has been measured before and after the correction to the spectral lines intensities. These corrections have been conducted against the self-absorption effect in order to demonstrate the accuracy in compressive strength measurements.

1.1. Measurement of plasma electron density

The importance of electron density (cm^{-3}) measurements relies on its ability to control the thermodynamical state of the plasma. It can be measured through different techniques, namely particle diagnostics (e.g., Langmuir probe method) or optical methods via optical emission spectroscopy technique (OES) [8].

The electron density measurement via optical emission spectroscopy entails different approaches such as the computation of the primary quantum number at the series limit [8,9], measurement of the optical refractivity of plasma [8,9], analysis of Stark profile of some primarily optically thin spectral lines [10], and measurement of the absolute emissivity of the continuum emission at the longer wavelength region of radiation [10].

Stark effect in plasmas is the result of the interaction of emitting atoms with an electric field generated by electrons in the plasma, leading to a broadening of the upper emitting state and shift. Among the OES methods proposed for electron density determination, the broadening of emission lines due to the Stark effect has been the most commonly used. This method is based on the assumption that the Stark effect is the leading broadening mechanism, in comparison with the Doppler broadening and the other pressure broadening mechanisms, due to collisions with neutral atoms namely resonance and Van der Waals broadenings [9,16].

The hydrogen Hα-line, the first affiliate of the Balmer series lines, is always exists in the LIBS spectra acquired in the open air and its appearance is pertinent to the humidity in ambient conditions. It was proposed in [13,17,18] that the precise electron density in the open air could be measured by using the Hα-line at the wavelength of 656.27 nm since the status on its optical thickness was examined and confirmed to be optically thin [17]. For hydrogenic elements, the linear Stark effect act on the total full width at half maximum. It causes a significant broadening which reduces the relative uncertainty of the measurement compared to the case of lines emitted by other elements. The theoretical calculations of this expansion of hydrogen lines parameters have been described in several investigations [8–10,19].

This linear broadening show itself on form of a Lorentzian line shape having a full width at half maximum $\Delta\lambda$ (H_α), hence, the plasma electron density can be deduced from the spectral broadening of the Hα-line using the following expression;

$$n_e\ (\mathrm{cm}^{-3}) = C(\lambda, T)(\Delta\lambda_{1/2})^{3/2} \tag{1}$$

whereas $\Delta\lambda$ is the full measured width at the half maximum of the H_α line in Å, C(λ, T) is a coefficient which depends weakly on electron temperature and density. It is tabulated by Griem [8].

On the other hand, this stark broadening is quadratic in case of element other than hydrogen which affects the Lorentzian half width The plasma electron density from the spectral broadening of the other lines such as calcium lines can be calculated using the following expression;

$$\Delta\lambda_s = [1 + 1.75A(1 - 0.75R)]\omega_s \frac{n_e(line)}{n_e^{ref}} \tag{2}$$

In this equation, $\Delta\lambda_s$ is the electron-impact half width, ω_s is the stark broadening parameter, A is the ion broadening parameter and n_e^{ref} is the reference electron density at which ω_s and A are calculated [20].

It is worth noting that, the Stark broadening of a separate non-hydrogenic neutral atom spectral line and ion is mainly due to micro-fields produced by the slow electrons. As a consequence, the contribution of quasi-static ions can be neglected, and hence Eq. (2) can be approximated to [22];

$$\Delta\lambda_s = \omega_s \frac{n_e(line)}{n_e^{ref}} \tag{3}$$

1.2. Measurement of plasma electron temperature

The interaction of high power pulsed laser with solids (for instance) releases heated plasma with temperatures altered from 6000–20,000 K. In which no measuring instrument could survive such considerably high temperature. A diversity of theories was developed for the measurements of plasma temperature [21]. Most of the spectroscopic temperature measurements are chiefly based on two methods. First, relative line intensities of either the same atom or ion, of neighboring ionization stages. Second, the successive isoelectronic ions; on relative continuum intensities, on ratios of line and continuum intensities [8,22,23]. The underlying assumption here is that the non-relativistic Doppler effects dominate over the other line broadening mechanisms [23]. The methods that are utilized to compute the plasma parameters (T_{ion}, T_{ex}, N_e, ..., etc.) lay on the assumption that the laser-induced plasma is