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# Mechanical properties and electromagnetic radiation characteristics of concrete specimens after exposed to elevated temperatures

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## HIGHLIGHTS

- We determine the feasibility of using electromagnetic radiation (EMR) to evaluate the condition of concrete after high temperature events.
- The mechanical properties of concrete are strongly influenced by exposure to high temperatures.
- Piezoelectric effects and motion from the variable velocity of charged particles are believed to be the probable mechanisms causing EMRs.

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## ABSTRACT

Experiments on electromagnetic radiation (EMR) from coal and rock under different loading modes have been conducted in laboratories and in the field, but there are few reports about EMR from concrete after it has been exposed to high temperatures. To determine the feasibility of using EMR to evaluate the condition of concrete after high temperature events, like structure fires, three groups of concrete specimens were tested by uniaxial compression after being heated to elevated temperatures; the EMR signals were recorded and analyzed. The results show that the compressive strength decreases with exposure temperature higher than 100 °C and the modulus of elastic is generally inversely proportional to exposure temperature. Low frequency EMR (~10.9–131.5 kHz) was observed during loading. The EMR impulses respond well to the stress, so they should reflect the stress state in the specimens. In our experiments, a large EM signal arrives that nearly coincides with the main fracture and then the signal rapidly attenuates; a series of low-amplitude oscillations follow. For specimens after being heated to different temperatures, the EMR waveforms are similar in shape but differ in intensity. The principal frequency and the corresponding maximum amplitude in the EMR spectra increase with the exposure temperature. Based on the exclusion method, piezoelectric effects and motion from the variable velocity of charged particles are believed to be the probable mechanisms causing EMR to be generated from the specimens.

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## 1. Introduction

The way in which concrete is damaged after it has been exposed to high temperatures is quite different from the damage that occurs under normal temperatures. In the international rock mechanics field, temperature has been regarded as an important factor affecting the mechanical properties of rock materials [1,2]. With the rapid development of China's economy, more and more infrastructure related to the development of geothermal energy, deep coal mines, and underground radioactive nuclear waste repositories needs to be constructed. In many cases, the effects of high temperatures on the physical and mechanical properties of the concrete used in the construction of these facilities needs to be considered [3,4]. In addition, evaluation of the mechanical properties of concrete after exposed to high temperatures is necessary for the restoration and reconstruction of structures after fires or even after wars. The stability of concrete after it has been subjected to high temperatures and the changes in the mechanical properties before failure is an important issue that needs to be investigated by rock mechanics research [4]. Therefore, studies of the deformation of concrete after subjected to high temperatures and evaluation of

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its mechanical properties are important theoretical and engineering endeavors. For this reason, many researchers have studied the performance of concrete after high temperature events.

Chan et al. [5] exposed specimens of normal strength concrete (NSC) and high-strength concrete (HSC) to temperatures up to 1200 °C and determined their compressive and tensile splitting strengths. Chan et al.'s results showed that HSC loses its mechanical strength in a manner similar to that of NSC and that temperatures between 400 °C and 800 °C were critical to the strength loss. Handoo et al. [3] fired concrete cubes prepared from ordinary Portland cement at temperatures up to 1000 °C in steps of 100 °C to investigate their chemical, mineralogical, and physical characteristics using X-ray diffraction and differential thermal/thermogravimetric analysis. Yu et al. [6] researched the mechanical properties of C40, C50 (NSC), and C80 (HSC) concrete exposed to high temperatures and discussed the effect of fire temperature, constant temperature over time, specimen size, cooling method, and concrete type on the concrete's mechanical properties. Arioz [7] studied the effects of elevated temperatures on the physical and mechanical properties of different concrete mixtures and found that the specimen's weight was significantly reduced after the specimen was subjected to high temperatures. In addition, the relative strength of the concrete decreased as the exposure temperature increased. By using a split Hopkinson pressure bar and high temperature resistance furnace, Xu et al. [8] conducted impact compression tests on concrete subjected to temperatures of 200, 400, 600, and 800 °C. They analyzed the influence of both temperature and the pressure bar velocity on the impact mechanical properties of the concrete and concluded that high temperatures had a significant effect on the performance of the concrete. The effects were especially significant for temperatures higher than 400 °C where several of the mechanical indexes changed.

In recent years, more and more studies, especially non-destructive ones, have focused on elevated temperature NSC and HSC damage assessment, such as scanning electron microscopy [3], ultrasonic acoustic waves [9], ultrasound P-wave and electrical resistivity [10]. However, these methods are only capable of comparing the state of the concrete exposed to fire or high temperatures before and after the heating experiment; they cannot study the concrete as its properties change during heating. Recording acoustic emissions (AE's) is believed to be a good method for continuously monitoring the rock materials' condition [11–15]. AE's has been used for assessment of concrete's internal damage, and good results have been achieved [16–19]. Although the AE method is a useful non-destructive method, it requires that the sensors be in contact with the concrete and this is somewhat inconvenient under some conditions. Therefore, it is desirable to use a non-contact method to assess the performance of concrete after subjected to elevated temperatures.

Electromagnetic radiation (EMR) was first put forward by Cohen in the 1920's [20] and EMR induced by material fracture was first observed by Stepanov in 1933 when he imposed a load on a specimen of KCl [21]. However, in subsequent years, the EMR method was not widely applied in materials science; EMR research was mainly focused on alkali halide crystal. Discoveries showed that when new dislocations and micro-cracks were generated, a charged layer would appear on the new crack surface and EMR could be excited [22,23]. Research on EMR from rocks started when seismologists discovered that, in some cases, electromagnetic anomalies appeared to be precursors for earthquakes. Vorarovich and Parkhomenko studied piezoelectricity in granite, gneiss, and vein quartz samples in the laboratory and recorded the light emissions [24]. Nitsan [25] and Xu et al. [26] also found piezoelectricity in rocks studied in the laboratory and this showed that electromagnetic waves can be generated by fracturing quartz and other piezoelectric materials. In recent years, EMR has been used successfully to monitor regional high stresses and predict natural and engineering disasters such as earthquakes, rockbursts, and coal and gas outbursts [27–31]. However, published research on the application of EMR to concrete, especially to concrete after exposed to high temperatures, is rare.

For this paper, three groups of concrete specimens were heated to 100–600 °C in 100 °C increments and then the EMR from the specimens after cooling under uniaxial compression. The research aims to investigate the feasibility of using EMR to evaluate the stress in concrete after exposed to high temperatures and to study EMR characteristics during compressive fracturing.

## 2. Experimental details

### 2.1. Specimen preparation

For this study, the concrete used was #42.5 Portland cement with the coarse and fine aggregate being crushed granite and local natural river sand with maximum nominal sizes of 20 mm and 0.5 mm, respectively. Concrete with a C25 strength grade was produced by mixing the components in a ratio of 1:3.79:3.04:0.59–Portland cement:crushed granite:sand:water by weight. The concrete mixture was prepared in a mixing pan. For the compression experiments, 30 concrete cubes were prepared. The cubes, roughly 150 mm on each side, were cast three at a time in 10 plastic molds. All the concrete specimens were allowed to set in the molds for 24 h and then removed from the molds and cured in water at 25 °C for 28 days. The specimens were then stored in an environmental chamber (25 °C) for an additional three weeks before testing.

### 2.2. Experimental system

#### 2.2.1. High temperature heating equipment

The high temperature heating equipment used was a QSH-1200 T box-type high temperature oven with a maximum operating temperature of 1200 °C and a heating rate of 0–30 °C/min. The oven was controlled by a 51-segment programmable intelligent temperature control instrument. This high temperature oven has the advantages of simple operation and high accuracy and includes an alarm for over temperature and a broken thermocouple.

#### 2.2.2. Loading system

The loading system used was a YAW4306 servo-controlled mechanical press with a DCS controller using the Power TestV3.3 controlling program. The YAW4306 employs closed loop control, constant stress control, and stress retention with a maximum load capacity of 3000 kN and a programmable loading speed between 600 and 60,000 N/s. Accuracy is ±1%. The loading equipment has two control modes, displacement and load force, which can be used for uniaxial compression, uniaxial tension, cyclic loading, or creep tests.

#### 2.2.3. EMR data acquisition system

Data were collected and recorded with an Express-8 AE System manufactured by PAC (Physical Acoustic Corporation, Princeton Junction NJ, USA). This system has 24 high-speed channels for real time AE and EMR data acquisition. The signals acquired by the electromagnetic antennas are amplified by the preamplifier and transmitted to the 16-bit A/D conversion module. The digital signals are stored in the buffer and subsequently transmitted to the computer for further processing and display.

A schematic diagram and photographs of the EMR testing system are shown in Fig. 1.

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