



# Characteristics of fulgurite-like structures under HV conditions: Effects on electrical earthing systems

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**Abstract**— Fulgurites are natural tubes of glass formed by the fusion of silica sand or rock from a lightning strike. The fulgurites have been produced artificially in HV conditions in the past. Recent studies have found that fulguritic structures can be formed in some other materials, such as bentonite and cement, as well. These fulgurites can change the overall physical and electrical properties of the original materials. Thus, formation of fulgurites can modify the performance of electrical earthing systems, both ordinary and those improvised with backfill materials. This study investigates the fulgurite formation under alternating, direct and impulse current application. Bentonite and sand were tested under high voltage conditions. The type of fulgurites and their effects on electrical earthing systems were studied by analyzing the resistivity and permittivity of original materials and fulgurites. It has been found that fulgurites formation has a severe effect on the earth resistance of grounding systems.

**Keywords**- Fulgurites, bentonite, resistivity, high voltage, impulse current  
*Introduction*

## I. INTRODUCTION

Lightning may cause transients with impulse currents of amplitude over 100 kA and duration around 70-100  $\mu$ s followed by continuing currents of below 1 kA that may flow for many hundred milliseconds [1]. Such lightning currents may carry sufficient energy and power to melt silica in sand, as the current is injected into ground. The melted sand fused into a dendritic or tubular form on cooling to form fulgurites [2, 3]. Artificial fulgurite were reportedly produced first by Pastor David Hermann in Germany in 1706 [4]. Triggered lightning experiments have produced fulgurites of very large dimensions, sometimes, in many meter lengths [5-6].

Fulgurites are natural tubes of glass formed by the fusion of silica sand or rock from a lightning strike. Their shape was formed by lightning bolt as it disperses into the ground [2, 3, 7]. Fulgurites are formed when all lightning strikes that hit the ground at a temperature of 18000 degrees Celsius to melt sand [2, 3]. All fulgurites can be divided into two categories which are sanded and rock fulgurites [3]. Sand fulgurites are generally found in beach or desert regions with dry sand. Such fulgurites are usually hollow, glass-lined tubes with sand adhering to the outside [5]. Rock fulgurites are formed when lightning strikes the bare surface of rocks. This type of fulgurite is normally found as veins on rock surface within the host rock [7]. Normally, rock fulgurites are found on the peaks of mountains.

In the recent years, laboratory experiments done on some other purposes has revealed that fulgurite-like formation is possible in materials other than sand as well under the application of high voltage waveforms [9-11]. Most prominent fulgurite formation has been observed during the alternative voltage testing for sand and bentonite and the researchers have attributed such to the material ionization in the high temperatures of backfill materials [9, 10]. It has been envisaged with physical appearance that that fulgurites may have physical and electrical properties quite different to those of their original materials. If it is such, then the fulgurite formation may have significant impact on the performance of earthing systems, both buried in soil and encased in backfill materials [11, 12]. As the previous experiments have not progressed further than reporting the observation of fulgurites under various materials under high voltage conditions, this work has been undertaken to fill the knowledge gap.

## II. METHODOLOGY

A 10-cm layer of sand, bentonite and a mixture of the two were separately applied alternating voltage (henceforth referred as AV), direct voltage (henceforth referred as DV) and impulse voltage (1.5 / 50  $\mu$ s lightning voltage impulse) by AC generator (100 kV), DC generator (100 kV) and Marx generator (450 kV) respectively. The materials were kept in a perspex container with aluminium plate that acts as the ground electrode, placed at the bottom of the container (Figure-1). HV has been applied in a rod-palme configuration. Temperature of the material surface has been measured immediately after the application of HV by a mini infrared thermometer gun (Fluke 62). The original material and the powdered form of the obtained fulgurites have been tested for their resistivity and permittivity by using the box method (by means of a pre-calibrated digital LCR meter). A Digital Thermo-Hygrometer was used for measuring the moisture content and humidity of the material. Materials used were sand, bentonite and sand bentonite mix. Experiment was repeated for an oven dry material and a material saturated with water.

For AV and DV applications an air gap of 1 cm was kept between the material surface and the high voltage electrode. In the application of impulse voltage the electrode was kept in contact with the material surface. After the application of each impulse (with breakdown), the surface was re-flattened as usually a crater is formed after the arc.

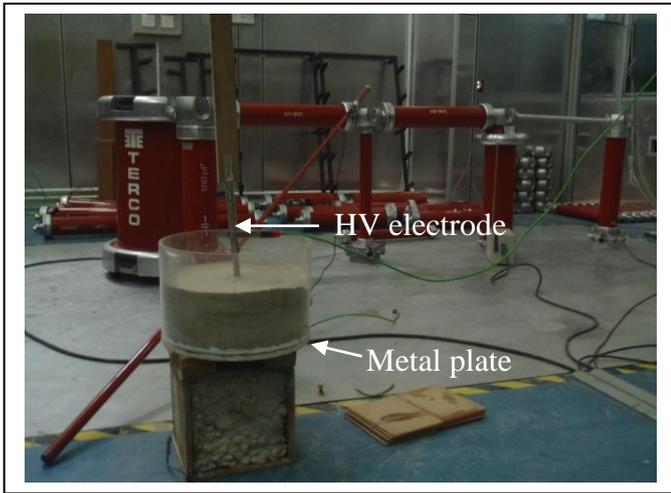


Figure-1: Arrangement of the electrodes and material

### III. RESULTS

Fulgurites were formed in all three materials in the application of DV. The voltage applied is approximately 10 kV on average for 5 minutes. Each experiment was repeated 10 times. The temperature of the surface immediately after the end of the application of voltage was around 140 °C – 225 °C with maximum and minimum values were recorded by bentonite and sand respectively. The Figure-2 depicts the fulgurites formed during this test. The largest fulgurites were formed with bentonite where the surface temperature is highest and the smallest was in sand where the temperature is lowest. Fulgurites formed in Bentonite and sand were more stable than that in the bentonite/sand mix. The fulgurites formed in the bentonite/sand mix has a tendency of being disintegrated on touch. It is apparent that the low resistivity of bentonite (much lower than sand) drives a large current during the application of the high voltage, which may be the reason for the formation of larger fulgurites and also resulting higher surface temperatures at the end of the application of voltage.

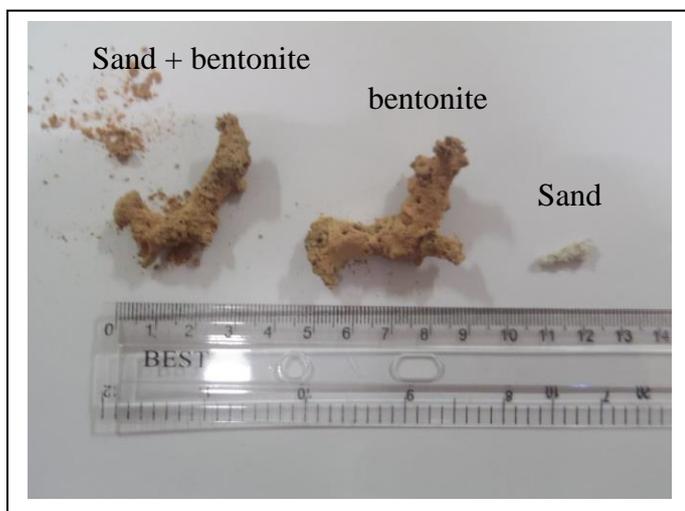


Figure-2: Fulgurites formed in DV test

The AV test with similar rms voltage values produced fulgurites only in bentonite where the surface temperature was recorded as about 240 °C on average. In the case of sand and bentonite/sand mix the temperature was in the order of 50 °C. The fulgurites formed in bentonite was also much smaller than that under DV conditions. A comparison of these fulgurites can be seen in Figure-3. The fulgurite formed with the application of AV in bentonite was lumpier than those developed under DV. The observations clearly indicated that the formation of fulgurites and their amount has a strong correlation with the temperature of the material just after the applications of the voltage waveforms.

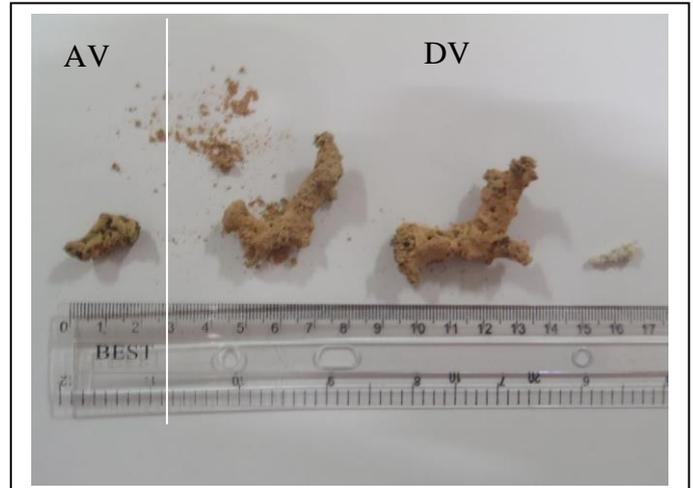


Figure-2: Comparison of fulgurites formed in DV test and AV test

None of the materials produced fulgurite-like structures in the application of the impulse voltage at 250 kV. As it was expected, the surface temperature also remained slightly above the room temperature.

Table-1 depicts the percentage increments in resistivity of the original material and its fulguritic form. The percentage increment in resistivity of the fulguritic form (in powdered form) with reference to its original material is in the order of 1367% for bentonite and 614% for mixture sand and bentonite. The amounts of fulgurites formed in the application of impulse voltages in all materials and that in sand under AV and DV were too little to make the measurements.

### IV. DISCUSSION

This experiment is specifically focused on the fulguritic formation in bentonite due to a specific reason. In the recent years, bentonite and bentonite based materials became highly popular as a backfill material among the engineers that work in the electrical earthing sector [10-15]. Bentonite is natural forming, pale olive brown clay which is typically acidic, having a pH value of 10.5 [11]. Therefore, it is a type of clay which has propensity to keep swells and water. The resistivity of bentonite can vary between few tens of Ohm meters (dry) to about 0.5 Ohm meters (wet) depending on the moisture content [10]. Dry bentonite is not known to have high corrosive effects on metals, however, the ability of the clay to attack iron and

steel (especially, low carbon steel) under wet conditions have been observed by the authors during the last few years of studies. Wet bentonite could shrink significantly leaving large voids between the solidified material and the surrounding. Additionally, the solidified bentonite shows many cracks once it becomes dry. Re-addition of water does not reduce the cracks or voids, instead widens the gap on re-drying.

The above observations on bentonite provide useful insight into the possible changes that may occur in the earthing systems that are surrounded by bentonite mixed materials. However, we may not make recommendations on the other materials used as ground conductance enhancement materials as the behavior of such materials under HV have not been studied so far.

Prior to the discussion on these changes, it is of interest to report regarding some observation made during the studies described in [11] and [12] for which two of the present authors were involved. During this experiment, in the event of applying AV and DV due to an operational failure in the over current tripping devices (identified much later) the voltage applied to the set up could be increased to a much higher than that in the present study. This may have resulted a much larger current being flown through the material. At the end of the experiment the material surface appeared red-hot for few seconds and it took nearly 10 minutes before the material could be handled by gloved hands (due to the high temperature). In that experiment the fulgurites formed were much larger (about 10 times that of the present study) and the formation was much more stable and rigid compared to the fulgurites observed in the present study. This observation shows that the formation of fulgurites has direct correlation with the type, magnitude and duration of the current through the material, which in turn correlates to the amount of heat generated.

The extremely high increment of resistivity of bentonite as it turns into fulgurite raises few doubts regarding the suitability of bentonite as it is as a earth resistance enhancement material. Note that the given values are resistivity of fulgurites in powder form. The bulk resistivity of the bentonite fulgurites and the soil containing such fulguritic formation may most probably be even higher than these values. The bentonite-sand mixture shows much lower percentage increment of resistivity, however, the absolute resistivity of fulgurites formed in the bentonite-sand mix is 60% more than that of bentonite fulgurites. Hence, it will be advantageous to develop ground resistance reducing agents mixing bentonite and other materials which generates less fulgurites under HV application and yet maintain low material resistivity.

It is also of interest to investigate the formation of fulgurites in the interface of sand and bentonite. Experiments are underway at present to find the behavior of the materials in such cases under high voltage impulses. It is envisaged that the fulgurites formed in such interfaces may significantly affect the physical continuity of the materials in contact. Under such circumstances one may observe increased earth resistance of earthing systems after prolonged earth fault currents and lightning currents of high magnitude grounding through the earthing system.

TABLE I. THE PERCENTAGE INCREMENTS IN RESISTIVITY OF FULGURITIC FORM OVER THE ORIGINAL MATERIAL

Material	Resistivity of original material ( $\Omega\text{m}$ )	Resistivity of Fulguritic form ( $\Omega\text{m}$ )	Percentage increment (%)
Bentonite	1.5	22	1367
Bentonite-sand	4.9	35	614

## V. CONCLUSIONS

Artificial fulgurites are formed in sand, bentonite and their mixtures under the application of direct voltage. The same results only in bentonite in the application of alternative voltage. The formation of fulgurites takes place when the voltage exceeds about 10 kV. The impulse voltage pulses, even at 250 kV did not result formation of fulgurites. The electrical properties of fulgurites in powder form are significantly different from those of respective original materials. As the increment is markedly high, it can clearly be concluded that fulgurites make the earthing systems perform quite poor, once such materials are formed. In their original shape, the value of bulk resistivity may be even higher. Therefore, the formation of fulgurites could undesirably enhance the ground resistance of an electrode system.

Note that the present experiment has been done under controlled laboratory conditions where the DC and AC magnitudes are controlled by supply tripping devices. However, in the event of earth faults in HV and MV systems much larger currents may flow into the ground through the earthing systems for prolonged periods if the earth fault tripping devices do not act properly. This may give rise to considerably large formation of fulgurites that could alter the total soil resistivity profile in the vicinity. The end result may be an unanticipated large value of ground resistance of the earthing system. In the lack of knowledge on the phenomena discussed in this paper the confused electrical engineer at the site may encounter a real challenge in making a forensic decision as to the reason of such sudden increment in ground resistance.

As we observe the regular fulgurite formation with bentonite and bentonite mixed materials under high voltage conditions, it is an important issue to be considered in using such substances as ground conductance enhancement materials in backfilling electrical earthing systems. However, the issue may be persistent with other materials used for the same purpose as well. Hence, it is of interest to repeat the investigations with other indigenous and commercially available ground resistance reducing agents as well.

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