Hindawi
Journal of Engineering
Volume 2022, Article ID 8181055, 5 pages
https://doi.org/10.1155/2022/8181055

Research Article

Experimental Determination of the Effect of Time of Exposure to Heat on Erosion Development in Different Soil Types

Emmanuel Emeka Arinze,[1] **Benjamin Nnamdi Ekwueme**,[2] **Jesuborn Obimba-Wogu**,[1] **and Ifedirichukwu Samuel Okeke**[1]

[1]*Geoenvironmental Engineering Research Group, Department of Civil Engineering, Michael Okpara University of Agriculture, Umudike, Abia, Nigeria*
[2]*Department of Civil Engineering, University of Nigeria, Nsukka, Enugu, Nigeria*

Correspondence should be addressed to Emmanuel Emeka Arinze; emmanuel.arinze@mouau.edu.ng

Received 10 May 2022; Revised 17 September 2022; Accepted 25 October 2022; Published 3 November 2022

Academic Editor: Paolo Castaldo

Tropical forests are increasingly exposed to devastating bushfires, leading to increased erosion. This work involves the study of the effect of exposure to heat on erosion development. Four different soil samples from the study area were used for the study. In this study, the postfire impacts of a laboratory fire representing a bushfire and a subsequent rainfall simulation experiment representing postfire rainfall were compared to evaluate the short-term impact of fire on heated bare soil. Laboratory observations show that bushfire or wildfire affects the erodibility of different types of soil. When the soil under consideration contains a meaningful amount of clay, initial exposure to heat tends to cement the soil sample, because clay minerals harden on exposure to bush burning. However, it is generally observed that at 6 hours of exposure to burning, the cementation is adversely affected, leading to increased soil loss.

1. Introduction

Bushfire fires are increasing in frequency and magnitude due to climate change and human activities, respectively [1]. Recent challenges and policy developments are opportunities for soil physicists and other soil erosion modellers to respond with more accurate assessments and solutions as to how to reduce soil erosion and how to achieve Zero Net Land Degradation (ZNLD) targets of 2030 [2, 3]. Therefore, determining the relationship between bushfire and erosion development is imperative in achieving ZNLD. Post-bushfire responses are basically transitory, incident, variable in space and time, dependent on intensity and severity, and involve multiple processes measured by different methods [4]. Forest fires are known to be one of the major causes of soil erosion, slope instabilities, land degradation, and sometimes debris flow [5–7]. These effects are felt both in temperate regions and in the tropics [8–10].

On-site effects are particularly evident on agricultural land where redistribution of soil particles within the area, loss of soil from the area, the breakdown of soil crumb, and the reduction in organic matter and nutrients lead to a reduction of cultivable soil depth and soil fertility. Erosion also leads to a decrease in soil moisture, which leads to a more drought-prone environment. The resultant effect is a loss of fertility vis-à-vis productivity and increased expenditure on fertilizer. Many countries spend so much on fertilizer, leading to an increase in the cost of agricultural products. According to Morgan [11], only 22% of the Earth's total field of 14,900 million hectares is conceivably productive. Since this has to provide 97% of the food supply, it is under rising constraint as the global population continues to surge.

Off-site problems emanate from sedimentation downstream, reducing the capacity of watercourses and drainage channels, enhancing the risk of flooding and blocking irrigation canals, shortening the design life of reservoirs.

Numerous hydroelectricity dams and irrigation projects have been rendered ineffective by erosion. Sediments have the potential to increase the levels of nitrogen and phosphorus in water bodies, leading to eutrophication. Erosion contributes to the weathering of soil aggregate into basic particles of sand, silt, and clay. The process of breaking down soil aggregate into primary particles results in the release of CO_2 into the atmosphere, aiding the greenhouse effect.

Forest roads are often subject to intense runoff and erosion and can be intensified by bushfires [12–14]. Their impacts on ecosystems are expected to increase in time due to changes in climate and land use [15]. It is therefore vital to mitigate the increased hydrological and erosive responses after wildfires to maintain the sustainability of ecosystems. Forests in the tropics are regularly subjected to severe fire outbreaks. Majorly, fire impact causes a meaningful effect on soil biophysiochemical properties. It also leads to vegetation damage, exposing the soil to erosion and land degradation [16]. These effects depend on the density of vegetation; the severity, size, and intensity of the fire; and the predominant soil type [4, 17]. Bushfire affects soil hydrology by breaking down the aggregated soil structure, decreasing moisture retention, developing water repellency (WR), and producing an oxidized ash layer [18, 19]. This in turn makes the soil susceptible to erosion. Many researchers have studied the causes, effects, and extent of fire-triggered soil erosion, ranging from laboratory studies to catchment studies [4], pointing to the common fact of increased soil erosion after bushfire or wildfire. These researchers have not been able to link the exposure to fire and subsequent erosion to the soil type with respect to engineering classification, and the time of exposure was not also considered in their studies.

The technique used in this study is to model the controlled experiment of soil heating (mimicking bushfire) and use subsequent rainfall simulations to determine the erodibility of the soil as described by Arinze et al. [20].

2. Materials and Method

2.1. Study Area. Soil samples (clay, top soil, sand, and laterite) were all collected from Umudike, Abia state, Nigeria. Umudike, the study area, is located within the tropical rainforest belt. The climate of the area is characterized by two main seasons: the rainy season and the dry season. The dry season originated from the dry northeasterly air mass of the Sahara Desert (Harmathan), while the rainy season originated from the humid maritime air mass of the Atlantic Ocean.

The rainy season spans from mid-April to mid-November, while the dry season spans from mid-November to mid-April. The rainy season is characterized by double maximum rainfall peaks in July and September, with a short dry season of about three weeks between the peaks known as the August break.

The study area Umudike and its environment is located within the central parts of Ikwuano-Umuahia which lies within 5028′645N and 5034′645N and longitudes 7031′602E and 7034′661E as shown in Figure 1.

Figure 1: Geographical map of study area (source: [21]).

2.2. Burning Treatments. Each soil sample was prepared in 8 different metal containers of dimensions ($50 \times 25 \times 5$ cm) at their bulk unit weight and natural moisture content to depict the in situ condition. The burning test was carried out under controlled laboratory conditions. Each of the prepared aforementioned soil samples was subjected to heat for 0 (control), 2, 4, and 6 hours using a furnace. This was done twice, each time to ensure a qualitative result. A maximum of 25°C was attained by using a thermocouple attached to the container, irrespective of the heating time.

2.3. Rainfall Simulation. In this study, a portable rainfall simulator designed and constructed by the Geo-environmental Research Group of the Department of Civil Engineering, Michael Okpara University of Agriculture, Umudike, was used. The metal container used for the burning treatment was placed under the rainfall simulator. A rainfall simulation took place for 2 hours per sample of soil. The soil box samples were subjected to a constant rainfall intensity of $30\,\mathrm{mm{\cdot}h^{-1}}$. The rainfall simulation experiment process was done twice for quality assurance. The runoff sediments were collected through a tank placed under the rainfall simulator, from which sediment concentrations were measured. The rainfall simulation in operation is shown in Figure 2.

2.4. Geotechnical Properties of Soil Sample. The specific gravity, natural moisture content, atterberg limit and sieve analysis were carried out according to ASTM D854-10 [22], ASTM D2216-10 [23], ASTM D4318-03 [24], and ASTM C136/C136-19 [25] specifications, respectively.

3. Result and Discussions

The basic geotechnical properties known as index tests were carried out as shown in Table 1.

For sand, soil loss decreased from 0 to 4 hours and increased from 4 to 6 hours. For loamy soil, the soil loss increased slightly from 0 to 2 hours and decreased from 2 to 6 hours. For clay soil, the soil loss decreased from 0 to 2 hours and increased from 2 to 6 hours. For laterite, the soil loss increased continuously from 0 to 6 hours of heating, Figure 3. The laterite recorded a nearly linear relationship

Figure 2: Rainfall simulation test of the heat-treated soil.

Table 1: Index properties of soils used for the study.

Property	Clay	Laterite	Sand	Top soil (loamy)
Specific gravity	2.52	2.55	2.60	2.40
Natural moisture content (%)	10.0	8.3	2.60	2.40
Liquid limit (%)	58	49	Non-plastic	29
Plastic limits (%)	30	28	Non-plastic	20
Plasticity index (%)	28	21	Non-plastic	9
Sand content (%)	58.5	64.0	98.36	50.0
Fine particle content (%)	41.5	36.0	1.65	50.0
Unified soil classification system	SC	SM	SW	CL

between the hours of exposure to bushfire and an increase in soil loss. In other words, as the time of exposure increases, the soil loss also increases.

The unheated soil used as a control and soil exposed for 6 hours witnessed the most soil losses. This shows that the decrease in soil losses during 2 hours and 4 hours of heating is due to the hardening of the soil minerals. However, as the heating continued for 6 hours, the cohesiveness began to deteriorate, resulting in increasing soil loss. The energy of transformation of heat and light with time causes some crystal structures to transit from one form to another [26]. The reason for this is that a crystal's maximum stability is at its crystallization temperature and time of exposure to heat. The structural stability reduces as the temperature goes below the crystallization temperature. Furthermore, because the heating was done at the temperature at which adsorbed water is affected, the heating and time of exposure impact the adsorbed water of the soil [26], affecting the soil characteristics.

Figure 4 demonstrates that sand had the most soil loss, while laterite had the least. Clayey, loamy, sandy, and lateritic soils recorded cumulative soil losses of 32, 36.7, 53.3, and 30.6 kg/m^2/hr, respectively. In the results given above, control was not considered because no heat was applied at that time. Because the geotechnical (index) properties in Table 1 reveal that the sand is not plastic, the low erodibility

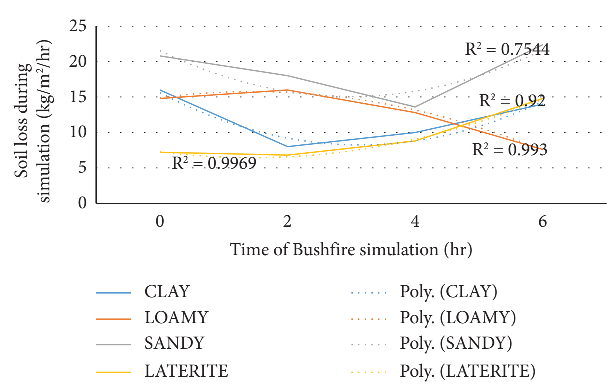

Figure 3: Soil loss vs. heating time.

of sand could be attributable to a lack of cohesiveness. Clay's cohesive characteristics and organic matter's colloidal qualities in loamy soil provided significant resistance to soil detachment in clay and loamy soil, respectively. Clay's cohesion provides resistance to soil separation, while coarse soil's large unit weight provides a barrier to transportation. Table 1 demonstrates that the lateritic soil contains a significant amount of clay minerals and sand that has been combined by nature. Laterite's synergistic blend of clay and

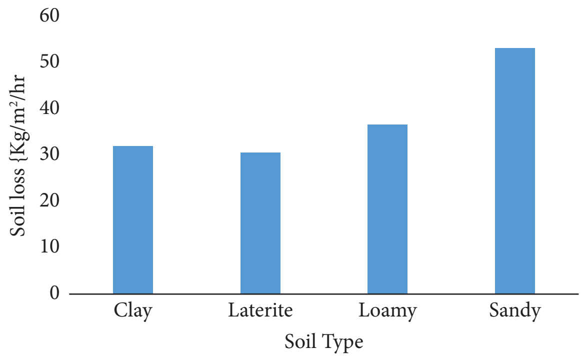

Figure 4: Cumulative soil loss (minus control) in each sample.

quartz minerals resisted soil loss. The heat helped these combined features by hardening the cementitious tendency of clay in lateritic soil that was reinforced by coarse particles.

4. Conclusions

The erodibility of different types of soil is affected by heat and the time of exposure to heat. When a soil sample contains a significant amount of clay, the first heat exposure tends to cement the soil sample, since clay minerals harden when exposed to heat. However, after 6 hours of exposure to burning, the cementation begins to give way, resulting in significant soil loss.

As the temperature rises and the time of exposure increases, the crystal structures of sand alter, resulting in a loss of adsorbed water in the soil, modifying its property in such a way that it substantially stimulates soil loss.

In the lateritic, fine and coarse soils are about equal. This could explain why it demonstrated a one-of-a-kind property in terms of the link between the time of exposure to heat and soil loss, with one increasing as the other did.

Finally, it is important to note that the burning period of 6 hours is key, as this is the time when all of the soil samples showed significant soil loss. The implication is that if a bushfire or wildfire occurs, it should not be allowed to burn for more than 6 hours, if possible.

Data Availability

The experimental data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest in the paper.

Authors' Contributions

E. E. Arinze handled conceptualization and experimental design. B. N. Ekwueme was in charge of the literature review. I.S Okeke and J. Obimba-Wogu conducted the experiment.

References

[1] E. L. Thomaz, "Effects of fire on the aggregate stability of clayey soils: a meta-analysis," *Earth-Science Reviews*, vol. 221, Article ID 103802, 2021.

[2] E. E. Arinze and C. C. Okafor, "Finite element method of stability analysis and stabilization of gully erosion slopes-a study of the otampa gully erosion site, otampa community, Isikwuato L. G. A., Abia state," *Journal of Civil & Environmental Engineering*, vol. 7, 2017.

[3] P. Panagos and A. Katsoyiannis, "Soil erosion modelling: the new challenges as the result of policy developments in Europe," *Environmental Research*, vol. 172, pp. 470–474, 2019.

[4] J. A. Moody, R. A. Shakesby, P. R. Robichaud, S. H. Cannon, and D. A. Martin, "Current research issues related to post-wildfire runoff and erosion processes," *Earth-Science Reviews*, vol. 122, pp. 10–37, 2013.

[5] E. Benito, M. E. Varela, and M. Rodríguez-Alleres, "Wildfire effects on soil erodibility in Galicia," *Cuadernos de Investigación Geográfica*, vol. 40, no. 2, pp. 353–370, 2014.

[6] L. Martini, L. Faes, L. Picco et al., "Assessing the effect of fire severity on sediment connectivity in central Chile," *Science of the Total Environment*, vol. 728, Article ID 139006, 2020.

[7] D. M. Staley, A. C. Tillery, J. W. Kean et al., "Estimating post-fire debris-flow hazards prior to wildfire using a statistical analysis of historical distributions of fire severity from remote sensing data," *International Journal of Wildland Fire*, vol. 27, no. 9, pp. 595–608, 2018.

[8] S. D. Keesstra, L. Wittenberg, A. Voogt, E. Argaman, and D. Malkinson, *Post-Fire Effects on Hydrological and Erodibility Factors in a Simulated Burn and Rainfall Experiment*, Geophysical Research Abstracts, Munich, Germany, 2012.

[9] R. Lal, "Soil erosion and sediment transport research in tropical Africa," *Hydrological Sciences Journal*, vol. 30, no. 2, pp. 239–256, 1985.

[10] D. Malkinson and L. Wittenberg, "Post fire induced soil water repellency-modeling short and long-term processes," *Geomorphology*, vol. 125, no. 1, pp. 186–192, 2011.

[11] R. P. C. Morgan, *Soil Erosion and Conservation*, Willey-Blackwell, Hoboken, NJ, USA, 3rd edition, 2005.

[12] M. E. Lucas-Borja and D. A. Zema, "Rill erosion in unpaved and rock-paved roads after wildfire in a mediterranean forest," *Geosciences*, vol. 11, no. 2, p. 79, 2021.

[13] I. Spanos, Y. Raftoyannis, P. Platis, and E. Xanthopoulou, "Post-fire management and recovery of a pine forest in Greece," *Web Ecology*, vol. 10, no. 1, pp. 27–31, 2010.

[14] L. Wittenberg, "Post-fire soil ecology: properties and erosion dynamics," *Israel Journal of Ecology and Evolution*, vol. 58, pp. 151–164, 2012.

[15] A. Girona-García, D. C. S. Vieira, J. Silva, C. Fernández, P. R. Robichaud, and J. J. Keizer, "Effectiveness of post-fire soil erosion mitigation treatments: a systematic review and meta-analysis," *Earth-Science Reviews*, vol. 217, Article ID 103611, 2021.

[16] R. A. Shakesby, "Post-wildfire soil erosion in the mediterranean: review and future research directions," *Earth-Science Reviews*, vol. 105, no. 3-4, pp. 71–100, 2011.

[17] J. E. Keeley, "Fire intensity, fire severity and burn severity: a brief review and suggested usage," *International Journal of Wildland Fire*, vol. 18, no. 1, pp. 116–126, 2009.

[18] L. F. DeBano, "The role of fire and soil heating on water repellency in wildland environments: a review," *Journal of Hydrology*, vol. 231-232, pp. 195–206, 2000.

[19] J. Mataix-Solera, A. Cerdà, V. Arcenegui, A. Jordán, and L. Zavala, "Fire effects on soil aggregation: a review," *Earth-Science Reviews*, vol. 109, no. 1-2, pp. 44–60, 2011.
[20] E. E. Arinze, B. N. Ekwueme, J. Obimba-Wogu, and I. S. Okeke, "Experimental determination of effect of bushfire on erosion development in different soil types," 2022, https://www.researchsquare.com/article/rs-1390441/v1.
[21] Maphill.com, *Geographical Map of Umudike*, Maphill, Lagos, Nigeria, 2013.
[22] ASTM D854, *Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer*, ASTM, West Conshohocken, PA, USA, 2010.
[23] ASTM D2216, *Standard Test Methods for Laboratory Determination of Water of Soil and Rock by Mass*, ASTM, West Conshohocken, PA, USA, 2010.
[24] ASTM D4318, *Standard Test Methods for Laboratory Determination of Atterberg Limits of Soils*, ASTM, West Conshohocken, PA, USA, 2003.
[25] ASTM C136/C136M, *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*, ASTM, West Conshohocken, PA, USA, 2019.
[26] J. K. Mitchell and K. Soga, *Fundamentals of Soil Behaviour*, John Willey & Sons, Inc, Hoboken, NJ, USA, 3rd edition, 2005.