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Chemical, Mineralogical, and Petrographic Analysis of the Mud Mortar from Fort Ikoma Historical Building in Serengeti National Park, Tanzania

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ABSTRACT: The restoration of historical buildings especially the Fort Ikoma in Serengeti National Park, Tanzania requires knowing the material properties used in their construction by characterizing the composition and properties of the mortar to inform the sustainable restoration strategies. Hence, the objective of this paper was to investigate the chemical, mineralogical, and petrographic analysis of the mud mortar from the Fort Ikoma historical building in Serengeti National Park, Tanzania using appropriate standard methods. The results indicated predominant compositions by weight of mud mortar through chemical analysis were silica (59.82%), alumina (20.42%), and Iron (III) oxide (11.07%), which contributed to the higher pozzolanic activity (91.31%) and cementitious properties (Cementitious Index of 46.76) of the historical mud mortar. Mineralogical analysis revealed that a high amount of quartz (38%), nacrite (17%), and other materials such as albite, chlorite, and nepheline put up the ability of mud mortar to resist environmental pressures. The findings contribute to awareness of historical building materials and provide the technical basis for restoring the Fort Ikoma historical building in Serengeti National Park, Tanzania, and similar historical buildings.

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Historical mortars, also known as traditional mortars, are essential in preservation, conservation, and restoration, serving as tangible links to our cultural identity and heritage. These materials have been used for centuries in the construction of buildings and monuments, contributing to their structural stability, breathability, and aesthetic appeal. Characterizing mortar-based materials provides valuable insights into the raw materials available at the time, construction techniques, hydraulic properties, and the cultural and natural context of a particular period (Triantafyllou *et al*., 2023). The analysis of historical mortars is performed for either conservation, repair, or compatible restoration of heritage buildings (M. Loke *et al*., 2020). Historical buildings pose numerous challenges for diagnosis and restoration because of limited construction records, diverse and variable materials, restricted access, and limitations on sample extraction, which hinder the use of modern technical standards and building codes (Cintra *et al*., 2024). The

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historical significance of Fort Ikoma, firstly constructed as a masonry fort by Germans and later utilized by British colonial and Tanzanian post-independence governments, underscores the need for its preservation. Historical masonry structures like Fort Ikoma often face risks such as material fatigue, environmental loads, and inadequate original construction techniques (Lourenço, 2002). The historical fabric of such buildings reflects the knowledge and experience of past builders, often devoid of modern scientific and engineering standards (Mustafaraj, 2013). Fort Ikoma, located in Serengeti National Park, Tanzania, serves not only as an architectural and historical landmark but also as a significant asset with potential economic benefits through tourism. However, the fort has deteriorated significantly due to prolonged neglect and structural weaknesses, necessitating a comprehensive assessment and restoration plan. The preservation and restoration of historical buildings hold paramount importance for maintaining cultural heritage and ensuring its transmission to future generations (Lucian, 2008). This research aims to assess and develop restoration strategies for the Fort Ikoma Historical Building in Serengeti National Park, Tanzania, focusing on the chemical, mineralogical, and petrographic analysis of the historical mud mortar used in its construction. Understanding the composition, properties, and performance of this mud mortar is crucial for developing sustainable restoration strategies that respect the historical and cultural significance of the building while ensuring its longevity. Mud mortar, an essential component in the construction of Fort Ikoma, has been used historically in various forms of masonry structures. Its composition, durability, and compatibility with other construction materials are crucial for the longevity and integrity of historical buildings (Elsen, 2006). The mineralogical and chemical properties of historic mortar-based materials (lime mortars) from the Cemetery of the Monastery of Pammegiston Taxiarchon in Boeotia, Greece were characterized by powder X-ray diffraction (XRD) with a Bruker D8 advance diffractometer and the data were evaluated with EVA® software provided by Bruker, and energy dispersive x-ray fluorescence (EDXRF) spectrometry with a Bruker AXS S2 Ranger XRF spectrometer respectively (Triantafyllou *et al*., 2023). Also, the Roman mortars (hardened masonry mortars) from the historical town of Mertola were characterized by optical microscopy, scanning electron microscopy (SEM) JEOL JSM – 6400 coupled with OXFORD energy dispersive spectrometer (EDS) x-ray detector, x-ray diffraction (XRD) conducted by a Phillips diffractometer with Co Kα radiation and a speed of 0.05°/s from 3 to 74°, 2θ, thermal analysis carried out by SETARAM TGA-DTA analyzer under argon atmosphere, with a heating rate of 10°C/min from room temperature to 1000°C, thin section and polished surface of the mortar prepared by vacuum impregnation with epoxy resin (Silva *et al*., 2004). Regrettably, there is limited information concerning the characterization of historical mud mortar through chemical, mineralogical, and petrographic analysis. This research employed modern analytical techniques such as X-ray fluorescence (EDXRF), X-ray diffraction (XRD), and reflected and transmitted light microscopy to characterize the historical mud mortar. The findings from this investigation will contribute to the growing body of knowledge on historical construction materials and to develop restoration strategies for historical buildings like the Fort Ikoma historical building in Serengeti National Park, Tanzania (Degryse *et al*., 2002). Therefore, the objective of this paper is to investigate the chemical, mineralogical, and petrographic analysis of the mud mortar from the Fort Ikoma historical building in Serengeti National Park, Tanzania.

MATERIALS AND METHODS

Description of the Study Area: Geographically, Fort Ikoma is located in the Ikoma ward of the Serengeti district in the Mara region (36M 0682369 UTM 9769712, Map Datum Arc 1960) as shown in (Fig. 1). It is one of many Forts built across Tanzania during the German colonial rule from 1885 to 1918. Unlike other German forts built in urban areas, the Fort Ikoma is situated in an area abundant with wildlife. Administratively, Tanzania National Parks (TANAPA) through Serengeti National Park (SENAPA) is the owner and overseer of the Fort.

The historical mud mortar was collected from two different positions based on the exposure to weathering conditions; a sample of 12 kilograms of Mortar taken from the top of the Wall that was exposed directly to the Rain and Sun (MWRS) and a sample of 12 kilograms of Mortar from the bottom of the same Wall that Not exposed directly to the Rain and Sun (MWNRS). The historical mortar samples were taken from the external and internal sides of the rubble masonry walls at various heights, widths, and locations to represent the construction skills used in the structure. All samples were taken with a trowel and photographed by GPS Camera which shows its location, date, and time. The samples were measured and tested in the laboratory at the African Minerals and Geosciences Centre (AMGC) for chemical properties, petrographic properties, and mineralogical properties (4 kilograms for each test). Both materials were ground and analyzed using EDXRF, reflected and transmitted light microscopy, and XRD to understand their chemical, mineralogical, and petrographic characteristics.

Sample Condition and Nature: The samples (MWRS and MWNRS) were reddish brown colored and composed of clay materials, angular to sub-angular silt to sand-sized grains of quartz and feldspars. The samples had a granular texture; their constituent grains were wonderful (about 0.001mm) and medium to coarse crystals. These samples were highly weathered and altered in this case a prolonged weathering and alteration of the silicate-bearing rocks led to the formation of clay-related minerals.

Chemical Characteristics Analysis: Chemical characteristics analyses were performed using a Rigaku NEX CG most advanced energy dispersive XRF (EDXRF) spectrometer and it is a non-destructive analysis. The Rigaku NEX CG is an Energy Dispersive X-ray Fluorescence (EDXRF) spectrometer for elemental analysis of Sodium (Na) to Uranium (U) in solid, liquid, and powder samples as well as thin film coatings on solid substrates. In EDXRF low energy "soft" X-rays (1-50keV) are emitted from an X-ray tube. These source X-rays enter the sample and cause the atoms in the sample to fluoresce their characteristic low-energy "soft" X-rays. These fluorescent X-rays are captured in a detector and counted by a multi-channel analyzer. The NEX CG software then calculates the concentration of each element present in the sample from Sodium to Uranium. A powerful and easy-to-use QuantEZ® software interprets XRF with a multilingual user interface.

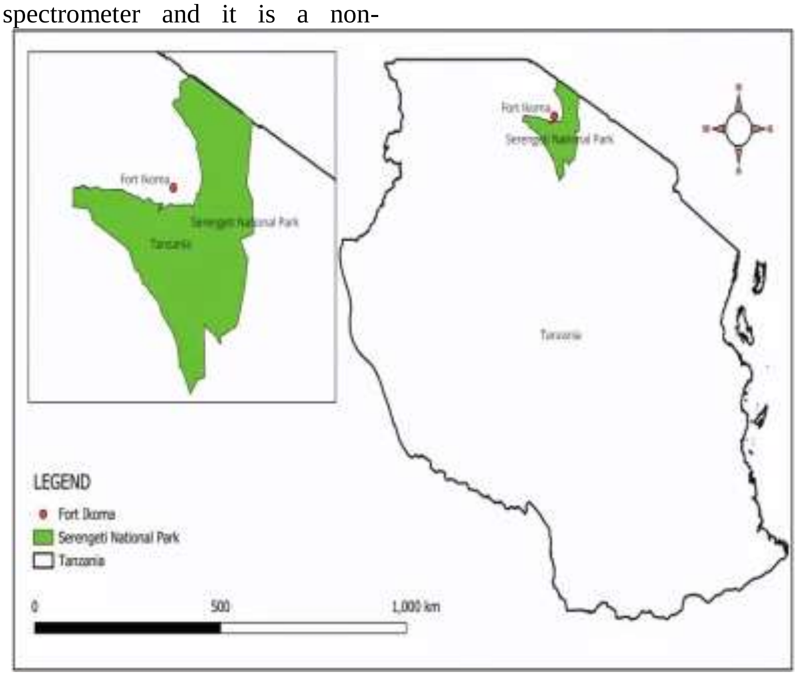

Fig. 1: Map showing the location of Fort Ikoma historical building in Serengeti National Park, Tanzania

Calibration of Rigaku NEX CG EDXRF spectrometer: The spectrometer machine was first calibrated using a Multi-Channel Analyzer (MCA) calibration sample to calibrate the relationship between the channels of spectrum data and energy of fluorescent X-rays and the standard results Fe=663keV, Ba= 470keV, and K= 356keV were obtained. Then the library calibration was conducted. In the library calibration, the peak profiles of elements are obtained using Sn, Cu, and SiO_2 samples, and the peak profiles are calibrated. The fluorescent X-ray intensities of elements contained in the MCA sample are also obtained to carry out the drift calibration of sensitivity library measurement intensities. If this calibration is not carried out for a long period, library data will not correlate with the data of samples because of variations in peak profiles and X-ray intensities, and erroneous identifications and shifts of analysis value will result. Afterward, sample pellets were loaded and analyzed on the EDXRF spectrometer. The obtained sample results were evaluated using NEX CG software, normalized, and finally printed for reporting.

Cementitious properties of the historical mud mortar

Pozzolanic Activity Analysis: Pozzolans are materials that contain siliceous or aluminous substances, which in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. The chemical composition requirements of natural pozzolan are approximately 70 % in the form of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3). All pozzolans have to be rich in reactive silica or alumina plus silica. The primary focus is on oxides such as SiO_2, Al_2O_3, and Fe_2O_3, which contribute to the material's pozzolanic activity and overall cementitious behavior. For the best cementitious properties, good pozzolan requires that the summation of SiO_2, Al_2O_3, and Fe2O3 should be greater than 70%, as shown in equation (1) (Justnes Harald Justnes *et al*., 2017).

$$\text{Pozzolanic activity} = SiO_2 + Al_2O_3 + Fe_2O_3 > 70\% \quad (1)$$

Cementation Index (CI) Analysis: The oxide percentages are useful for the calculation of the Cementation Index (CI), this index was used to assess the hydraulicity of the mud mortar according to the Boynton formula as indicated in Equation 1 (M. E. Loke *et al*., 2020) and (Ponce-Antón *et al*., 2020). For mortars with unknown binders, the calculation of the hydraulicity helps in classification (Lindqvist *et al*., 2006). The higher the index, the more mortar has hydraulic properties.

$$CL = \frac{(2.8 \times \%\text{SiO2} + 1.1 \times \%\text{AI2O3} + 0.7 \times \%\text{Fe2O3})}{(\%\text{CaO} + 1.4 \times \%\text{MgO})} \quad (1)$$

Where: CL = Cementation Index; SiO_2 = silicon oxide, Al_2O_3 = aluminium oxide, Fe_2O_3 = iron oxide, CaO = calcium oxide; MgO = magnesium oxide

Equation (2) is mainly used for natural hydraulic limes but can be used to get an indication of the type of binder used when analyzing an unknown mortar type. Calculated CI values are shown in (Table 1).

Table 1: Cementation index readings (M. E. Loke *et al*., 2020)

Binder description	CI	Active clay in the limestone
Fat limes	Close to zero	-
Pure (aerial) lime	CI < 0.15	Very little clay
Sub-hydraulic lime	0.15 to 0.3	Very little clay
Slightly hydraulic limes	0.3 to 0.5	Around 8%
Moderately hydraulic limes	0.5 to 0.7	Around 15%
Eminently hydraulic limes	0.7 to 1.1	Around 25%
Natural cement	1.7	Up to 45%

Mineralogical Characteristics Analysis: Mineralogical characteristics analyses were conducted at ambient temperature using a Rigaku MiniFlex benchtop X-ray diffractometer. The applied equipment conditions were Cu-Kα radiation, λ = 1.5405 Å, from 3º to 70º (2θ) explored range, 0.11º 2θ/s scanning rate. Its XRD patterns were interpreted using the latest SmartLab Studio – II software, Rigaku's full-function powder diffraction analysis package. The software provides various analysis tools such as automatic phase identification, quantitative analysis, crystallite-size analysis, lattice constants refinement, Rietveld analysis, and ab initio structure determination. The powder sample was sieved at 53 microns and analyzed by using the XRD method to detect the type of clay materials and the general mineral composition of the historical mud mortar.

Petrographic Characteristics Analysis: Petrographic characteristics analyses were executed using Leica reflected and transmitted light microscopy. A petrographic or thin section was used to analyze a sample of a historical mud mortar from the Fort Ikoma historical building. The thin sections were analyzed using a Leica DM 750P polarizing light microscope.
The petrological analysis helped us to determine the optical features of the clay materials related to quartz, plagioclase, and K-feldspars by identifying the mineral composition, type and quantity of minerals inclusions and alterations, important microstructural, textural of waterproofing materials samples, and some of the optical characteristics that can be observed for the fibrous materials in this sample.

Vacuum Impregnation: The procedure used for all samples that have loose grains such as quartz sand, soil highly weathered rocks, and rock aggregate whereby easy to break and split in the direction of the grain orientation. It involves the use of a vacuum pump, epoxy resin, and hardener at a ratio of 100:45 respectively. Thus, the historical mud mortars were vacuum-impregnated before thin section preparation.

Two different standard samples of thin sections were prepared from each historical mud mortar for the maximum representation of the information. Then, the thin sections of standard 30 microns were made ready for petrographic analysis.

Thin Section Sample Preparations: The rock chips resulted from vacuum impregnated of 4-5mm were cut by diamond impregnated cutting saw from big to small size rock samples (rock chips), then rock chips were clearly labeled, dried, and mounted onto glass slides so that two different standard petrographic thin sections were prepared from each sample by using standard procedure for preparing thin section.

Illustration Images: The images were taken with a Leica camera at X50 magnification, several images were taken at x100 magnification depending on the features observed. The images were taken at the 1600 x 1200 pixels size at a calibration of 1 pixel = 1 pixel. The field of view for all samples is 7mm.

RESULTS AND DISCUSSION

These results were evaluated through EDXRF, X-ray diffraction (XRD), and reflected and transmitted light microscopy tests.

Chemical characteristics: The table (Table 2) presents the chemical composition analysis results for two historical mud mortar samples, MWRS and MWNRS, from the Fort Ikoma historical building. The results were provided as percentages for various oxide compounds. The main chemical constituents of the historical mud mortar were silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), iron (III) oxide (Fe_2O_3), calcium oxide (CaO), potassium oxide (K_2O), magnesium oxide (MgO), and titanium dioxide (TiO_2), with average proportions of approximately 59.82%, 20.42%, 11.07%, 2.24%, 1.94%, 1.42%, and 1.24%, respectively. The historical mud mortar mainly contained 58.69% - 60.94% SiO_2, 19.91% – 20.92% Al_2O_3, 10.45% - 11.69% Fe_2O_3, 1.86% - 2.61% CaO, 1.91% - 1.97% K_2O, 1.03% - 1.81% MgO, and 1.22% - 1.26% TiO_2. The results showed that the historical mud mortar was predominantly composed of silica (SiO_2), alumina (Al_2O_3), iron (III) oxides (Fe_2O_3), and smaller amounts of calcium, potassium, magnesium, and titanium oxides. These chemical compositions reflected the natural clay and soil materials used in the mortar's preparation.

The small difference in the oxide percentages between the MWRS and MWNRS samples could be attributed to factors such as exposure to weathering, sampling location, or inconsistency in the mortar mixture across the building. The high silica (SiO_2) and alumina (Al_2O_3) content, averaging around 59.82% and 20.42% respectively, recommends that the mortar had a large amount of clay minerals present. These aluminosilicate clay minerals contribute to the binding and cementitious nature of the historical mud mortar through pozzolanic reactions. The potassium oxide (K_2O) at 1.94% and magnesium oxide (MgO) at 1.42%, contributed to the reactivity and binding characteristics of the mortar.

The occurrence of calcium oxide (CaO) at around 2.24% on average showed the potential presence of some lime (calcium-based binder) in the historical mud mortar mixture. The chemical composition of the mortar of historic buildings in Bagamoyo, Tanzania contained a low percentage of CaO (27.52%) indicating that was not pure hydraulic lime but hydrated lime (quick lime) or air-hardening lime (Lucian, 2015). The iron oxide (Fe_2O_3) content, averaging 11.07%, contributed to the color and durability of the historical mud mortar.

The study of historical lime mortar conducted by (Loureiro *et al*., 2020), indicated that chemical composition had a high concentration of SiO_2 (46.5-84.4%), CaO (2-2.24.9%), Al_2O_3 (1.8-5.8%), and Fe_2O_3 (0.3-1.2%), besides the highest level of SiO_2, were identified in the building of the late 19th century and CaO in the older mortars. SiO_2 and CaO were the elements observed in other studies of historical mortars and confirmed that the quartz aggregate was predominant. Fe_2O_3 contributed to the beige color of the mortar. The low content of Mg showed that calcium lime was used in the mortars.

Table 2: Chemical compositions for MWRS and MWNRS (% by weight)

Sample Identity	**SiO_2 %**	**Al_2O_3 %**	**Na_2O %**	**K_2O %**	**Fe_2O_3 %**	**MgO %**	**CaO %**	**SO_2 %**	**TiO_2 %**	**P_2O_5 %**	**BaO %**	**MnO %**	**SrO %**	**CI %**
MWRS	60.94	19.91	0.77	1.97	10.45	1.03	2.61	0.3	1.26	0.41	0.08	0.26	<0.01	<0.01
MWNRS	58.69	20.92	0.8	1.91	11.69	1.81	1.86	0.25	1.22	0.35	0.09	0.25	<0.01	0.13
Average%	**59.82**	**20.42**	**0.79**	**1.94**	**11.07**	**1.42**	**2.24**	**0.28**	**1.24**	**0.38**	**0.09**	**0.26**		

NB: <0.01% means the parameter reading is less than the lowest detection limit which is 0.01%

Cementitious properties of the historical mud mortar

Pozzolanic Activity: Historical mud mortar indicated higher pozzolanic activity and cementitious properties of 91.31%. A pozzolanic activity above 70% is qualified as indicative of good pozzolanic materials (Widodo *et al*., 2015).

Cementation Index (CI): The calculated CI value of 46.76 was very high compared to Table 3 values. The high CI suggested that the historical mud mortar had a strong potential for cementitious behavior (Pinho Figureueiredo *et al*., 2016).

Mineralogical characteristics: The samples were analyzed by X-ray diffraction method and the results are shown below (Table 3):

Table 3: Mineralogical compositions for MWRS and MWNRS

	Mortar Composition		**Sample Name: MWRS**		**Sample Name: MWNRS**	
S/N	**Name**	**Formula**	**Major Volume %**	**Minor Volume %**	**Major Volume %**	**Minor Volume %**
1	Quartz	SiO_2	38		34	
2	Nacrite	$Al_2Si_2O_5(OH)_4$	17		15	
3	Chlorite	$(MgFeAl)_6(SiAl)_4O_{10}(OH)_8$	8.6			2.6
4	Albite	$NaAlSi_3O_8$	6.5		7	
5	Nepheline	$(NaK)AlSiO_4$	6.1			3.1
6	Hematite	Fe_2O_3	6		7	
7	Goethite	FeO (OH)		3.4		
8	Amesite	$Mg_2Al_2SiO_5(OH)_4$		3.3	8	
9	Berlinite	$AlPO_4$		3.2		
10	Rutile	TiO_2		2.8		2.3
11	Biotite	$K(MgFe)_3(AlSi_3O_{10})\ (FOH)_2$		1.4		1.6
12	Sillimanite	Al_2SiO_5		1.2		1.4
13	Phlogopite	$K_2Mg_6(Si_6Al_2O_{20})\ (OH)_4$		1.1		
14	Siderite	$FeCO_3$		0.8		
15	Alarsite	$AlAsO_4$		0.6		
16	Orthoclase	$KAlSi_3O_8$			6.5	
17	Chloritoid	$(FeMgMn)_2Al_4Si_2O_{10}(OH)_4$			5.4	
18	Lepidocrocite	FeO (OH)				2.9
19	Lazulite	$(MgFe_2)\ Al_2(PO4)_2\ (OH)_2$				1.2
20	Magnetite	Fe_3O_4				1
21	Muscovite	$KAl_2(AlSi_3O_{10})\ (FOH)_2$				1
	Total Percentages		**82.2**	**17.8**	**82.9**	**17.1**

Mortar taken from the top of the Wall that was exposed directly to the Rain and Sun (MWRS): The presence of 38% of quartz and 17% of nacrite in a sample, showed the use of durable and plastic materials that contribute to the structural integrity of the Fort Ikoma building under worse environmental conditions. Mud mortar's stability against weathering, flexibility, and chemical resistance contributed by the chlorite (8.6%) and nepheline (6.1%). The compositions were appropriate for the historical mud mortar to alleviate the effects of chemical degradation, thermal expansion, and moisture penetration. For restoration purposes, replicating MWRS should involve the inclusion of these critical minerals to ensure the restored mortar can withstand similar environmental stressors. The presence of berlinite (3.2%) and unique iron oxides like goethite (3.4%) and siderite (0.8%) further support the need for formulations that enhance durability and weather resistance. These elements contribute to the color stability and overall robustness of the mortar, which are vital for preserving the aesthetic and structural integrity of exposed surfaces.

Mortar taken from the bottom of the Wall that was Not exposed directly to the Rain and Sun (MWNRS): MWNRS, containing 34% quartz and 15% nacrite, shares similar foundational components with MWRS but diverges significantly in its additional mineral content. The higher presence of amesite (8%) and orthoclase (6.5%), as well as the unique inclusion of chloritoid (5.4%) and lepidocrocite (2.9%), indicates a focus on optimizing the mortar for internal stability and protection from internal humidity rather than external weathering. These minerals contributed to the hardness, thermal stability, and resistance to biological growth, which were crucial for mortars used in protected or interior environments. Restoration efforts for sheltered areas should aim to replicate MWNRS's composition. This approach will ensure that the restored mortar maintains the original characteristics, providing appropriate internal structural support and preventing deterioration due to internal environmental factors. The use of muscovite (1%) and lazulite (1.2%) in MWNRS highlights the need for minerals that enhance the mortar's resilience against internal moisture and potential biological effects**.** While mineralogical analysis of the lime mortars of the historical buildings in Belém do Pará, Northern Brazil founded in 1616, indicated that quartz was used as aggregates which was the common mortar to that period, quartz, calcite, and kaolinite was the main mineral phases (Loureiro *et al*., 2020). Moreover, according to (Triantafyllou *et al*., 2023) the mineral phases observed were calcite ($CaCO_3$), quartz (SiO_2), albite ($NaAlSi_3O_8$), illite ($(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}((OH)_2,(H_2O))$), muscovite (KAl2(AlSi3O10)(F,OH)2), clinoclore (Mg5Al(AlSi3O10)(OH)8), kaolinite (Al2Si2O5(OH)$_4$), montmorillonite ($(Na,Ca)_{0.3}(Al, Mg)_2Si_4O_{10}(OH)_2\cdot n(H_2O)]$, and microcline ($KAlSi_3O_8$). Classified as a pure lime air binder due to the presence of calcite.

Petrographic characteristics

General Descriptions: Mineral Assemblage: The soil samples were very fine-grained, 15-20% Clay, inhomogeneous, poorly sorted angular to subangular, round to sub-round silt to sand-sized quartz, and other inclusions. Immature fragments composed mainly of clay materials, coarse to fine crystals of silt to sand-sized angular grains of quartz (some stained with iron oxide), highly altered feldspar (colorless, with grey interference colors), opaque iron oxide and hydroxide grains mainly hematite and goethite, lepidocrocite intergrown with quarts and weathered feldspar and clay matrix. Few flakes of mica minerals mainly biotite and muscovite were observed.

Inclusion: Inclusions were mainly of quartz subordinated with highly weathered perthitic K-feldspar and plagioclase feldspar fragments, very few muscovite, and biotite. Few grains of iron oxide and hydroxide mostly, goethite, hematite, and magnetite with very few altered siderite crystals.

Descriptions: The soil samples were reddish brown and characterized by coarse to fine silt crystals to sand-sized angular grains of quartz, and clay minerals due to a high amount of aluminium. The reddish-brown color of these red soil samples was due to the presence of iron oxide and hydroxide minerals such as goethite, hematite, and magnetite which were observed to be isotropic in the microscope. The red soil samples were characterized by having highly weathered feldspar grains which was a source of clay materials in this sample. Clay was a fine-grained natural soil material containing minerals such as nacrite, amesite, and chlorite in the samples. It is formed by prolonged chemical weathering of silicate-bearing rocks such as feldspars. The soil samples had grains that varied in size and shape. Quartz crystals in the samples were round to sub-round indicating transportation from a certain distance. The samples had occasional mud-sized iron oxide patches (isotropic at Plane Polarized Light (PPL)) stained lithic fragments. Phosphate-related materials such as berlinite were observed in the sample MWRS, these materials were due to the interaction of living organisms. The muscovite mica was the high-order-colored strands and strong pleochroic with basal to perfect cleavage, with the brown grains being biotite mica. Muscovite was colorless at PPL and showed high birefringence at Cross Polarized Light (XPL) while Biotite was brown at PPL. The biotite and muscovite, flakes were randomly oriented. The grey and colorless grains were quartz and weathered feldspar.

The descriptions of MWRS shown in (Fig. 2) were;
MWRS (a): Highly weathered plagioclase feldspar grain (colorless at PPL with grey birefringence at XPL). Round quartz crystals stained with iron oxide with coarse hematite crystals with several inclusions.
MWRS (b): Iron oxide melt showing flow texture surrounding and enclosed in the clay materials groundmass, very few fine flakes of mica (pinkish blue muscovite) were observed.
MWRS (c): Angular quartz crystals stained with opaque iron oxide floating in a clay groundmass, highly weathered perthitic K-feldspar grains.
MWRS (d): Highly weathered plagioclase feldspars grains stained with iron oxide, and quartz crystals, and few voids were observed to be filled with clay materials and quartz grains.

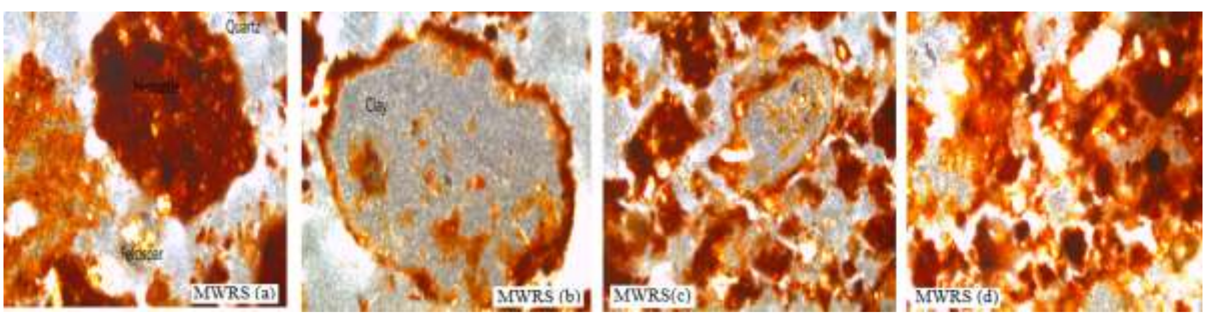

Fig. 2: The images description of MWRS

The descriptions of MWNRS shown in (Fig. 3) were;
MWNRS (a): Fine to medium, angular to subangular quartz crystals, iron oxide (reddish brown to black hematite), highly weathered plagioclase feldspar grains, and clay materials were observed in this sample.
MWNRS (b): Color band fabric of iron oxide magnetite (black), hematite (reddish brown), weathered perthitic K-feldspars crystals, angular to subangular quartz crystals, and the void filled with clay materials.
MWNRS (c): Sericitized feldspar highly weathered perthitic K-feldspar, discount fractures It is invaded with iron oxide melt. Quartz crystals stained with opaque iron oxide floating in a clay groundmass.

MWNRS (d): Poorly sorted fine to medium quartz grains, void, biotite, and discontinuity fracture. Extremely weathered plagioclase feldspars grains stained with iron oxide, clay materials masked by iron oxide.

The quartz crystals in MWRS were predominantly round and angular, stained with iron oxide, and the groundmass and voids were filled with clay materials. The textural features, including flow textures and secondary minerals like muscovite, indicate a dynamic and harsh weathering environment. In MWNRS, iron oxide (hematite and magnetite) is less extensive, and the quartz crystals were more stable, being angular to subangular. Clay materials were present but less masked by iron oxide compared to the MWRS samples. The textural features, such as the color band fabric of iron oxide, voids filled with clay, and poorly sorted quartz grains, suggested a more stable environment with less dynamic weathering processes. Rock grains in the sample MWNRS were greater than in sample MWRS, most of the tiny rock grains were observed to be angular to sub-angular, this gives us a clue that the soil was from a secondary geological environment due to transportation from a certain distance. According to the study conducted by (Loureiro *et al*., 2020), petrographic analysis in thin sections indicated that the presence of sub-rounded to sub-angular quartz grains of different sizes in a high birefringence matrix used as a binder and clay minerals perhaps related to calcite and found dispersed in the matrix that turns into brownish color.

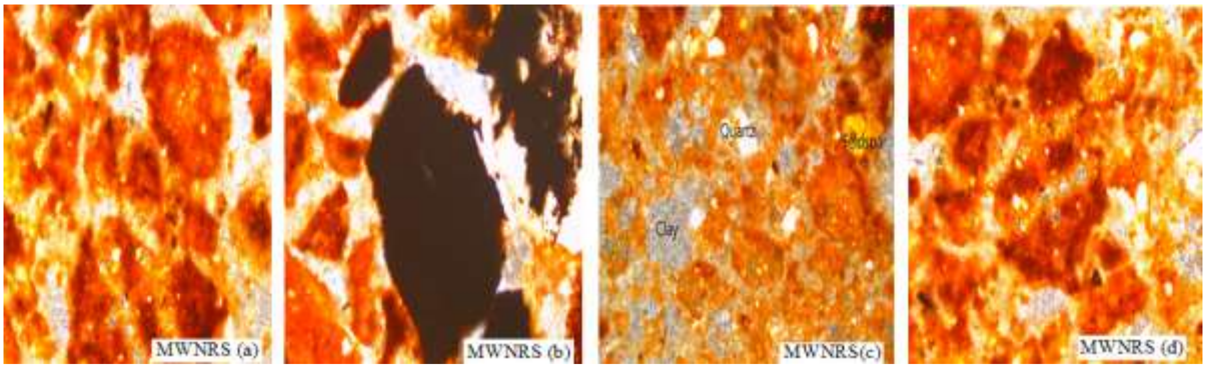

Fig. 3: The images description of MWNRS

Conclusions: Data obtained revealed mainly the presence of clay materials contributing to the mud mortar's binding properties through pozzolanic reactions. Also, richer proportions of chlorite, nepheline, berlinite, and specific oxides like goethite and siderite in MWRS develop the mud mortar's flexibility, resistance, and durability against weathering. The mud mortar's thermal stability, hardness, and resistance to internal humidity and biological growth contributed by the presence of a higher composition of amesite, orthoclase, chloritoid, lepidocrocite, and unique minerals like muscovite and lazulite in MWNRS. MWRS showed extensive weathering, characterized by highly weathered plagioclase and k-feldspar grains extensive iron oxide staining, and the presence of course hematite crystals, MWRS showed less weathering. It is recommended that the restoration of the Fort Ikoma historical building in Serengeti National Park, and similar historical buildings, should involve using natural clay and soil materials richer in silica, alumina, and Iron (III) oxide for the exposed surface of the building. Besides, mud mortar that contains higher amounts of chlorite, nepheline, goethite, and berlinite could be used for exposed surfaces. For internal walls and all sheltered surfaces, should include higher composition amounts of amesite, orthoclase, chloritoid, lepidocrocite, and muscovite as these show good structural integrity and less extensive weathering. These analyses help in identifying the primary original materials and providing a scientific basis for restoration purposes.

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Data Availability Statement: Data are available upon request from the corresponding author or fourth author.

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