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## Assessment of properties of rubble masonry used in heritage structure

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Article Info	Abstract
<p><b>Article history:</b></p> <p>Received 24 Aug 2023 Accepted 09 Dec 2023</p> <hr/> <p><b>Keywords:</b></p> <p>Heritage structure; Rubble masonry; Lime mortar; Surkhi</p>	<p>Preservation of Heritage structures is of utmost importance. Rubble masonry played a significant role in the conservation of structures. It is a traditional wall construction material used to build walls and standing structures in India since ancient times. Even now, heritage structures are being made to serve humanity for many years. Therefore, it is necessary to find a combination of rubble masonry and essential additives like lime mortar and surkhi to help build new heritage structures and also help reduce the deterioration of ancient architectural structures and monuments. This experimental study presents rubble masonry for repairing Heritage structures as an alternative to the conventional use of cement mortar. In addition to repairing work, rubble masonry, lime mortar, and surkhi are used to build new heritage structures for long-term sustainability. Rubble masonry, lime mortar, and surkhi can reduce the deterioration of old architectural structures and monuments. A case study on Global Vipassana Pagoda allocated in Mumbai, India, is considered. It is made up of Basalt stone with an interlocking system.</p>

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### 1. Introduction

India is known for its rich history and significant heritage structures. As per the archaeological survey of India, in the present day, India has 3650 ancient monuments and archaeological sites and remains of national importance, whereas world heritage sites count is 1157. Indian heritage structures are three times more than the world heritage sites, and one or more new structures are discovered whenever some major excavation happens. India carries greater responsibility for preserving these structures with efficient material which is environmentally friendly, sustainable, and does not damage the structure after repair. Even when a new heritage structure is being constructed, one must have material similar to the material used in ancient structures in India; this particular work is focused on creating such material. The author found that rubble masonry along with lime mortar and surkhi gives such a combination, which is very effective in preserving ancient heritage structures in India and can also be used to construct a new heritage structure. This study involves an experimental investigation of rubble masonry commonly employed in heritage structures such as the Pagoda in Gorai, Mumbai, India. In the Pagoda dome, rubble masonry serves as infill material, facilitating load transfer from the superstructure to the dome's foundation. Given the dome's shell-like structure, the forces acting on this rubble masonry are primarily compressive. This study highlights the lasting potential of using rubble masonry with lime and surkhi mortar in building and preserving historical structures, exemplified by the Global Pagoda Vipassana in Mumbai, India. Heritage

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structures play a vital role in safeguarding history and cultural heritage, and rubble masonry remains a durable construction method. It has effectively contributed to the construction of historical structures throughout various eras, underscoring its strength. Further this research underscores the importance of a well-balanced composition, which involves combining rubble masonry with additives like lime mortar and surkhi to ensure structural longevity. Additionally, it emphasizes the environmentally friendly aspect of this traditional construction technique, offering a sustainable alternative to conventional cement mortar. The case study of the Global Vipassana Pagoda in Mumbai serves as a compelling real-world example of the successful application of this approach.

A case study on Global Vipassana Pagoda, Mumbai, is considered in this study (See Fig. 1 (a) and (b)). It is located in Mumbai, India. It is located in the North of Mumbai on a peninsula between Gorai Creek and the Arabian Sea. The foundation of the dome was done with basalt stones. The general stratigraphy of the west coast of Mumbai is primarily composed of basalt rock with minimal overburden. The subsurface layers consist mainly of dark brown and highly fractured basalt rock with varying degrees of weathering. Mineral-filled fracture planes are common in the basalt. Some locations have a limited overburden of marine clay or silty sand. Highly fractured zones exist below the intact rock mass, and volcanic breccia with lapilli tuff is observed in the Back Bay area. Lapilli tuff exhibits varying degrees of weathering, with fracture planes filled with minerals. [1-2] Geological processes have led to the mixing of mafic and felsic melts in Mumbai's Manori-Gorai area, potentially forming rocks with intermediate characteristics.[3]



Fig. 1. (a) Global Pagoda Vipassana, (b) Location on Google map

### 1.1. Literature Review

The following literature review provides a comprehensive understanding of the role of rubble masonry, mortar in heritage preservation and the diverse research efforts to address the challenges and opportunities associated with this critical component of historic structures.

Mortar is a binding material [4] which keeps the building blocks of standing structures together by providing strength and durability. Lime and gypsum mortars have been used in India for thousands of years. Today, cement mortar is used extensively in all modern buildings. Cement mortar encourages dampness and can destroy heritage structures that have stood for hundreds of years. It can also alter the appearance of the original structure; cement mortar may not be compatible with the original mortar used during the

construction of heritage structures, and cement mortar causes loss of breathability. Historic structures were designed to be breathable, allowing moisture to pass through the walls and evaporate, which helps prevent moisture-related damage. Cement mortar is less permeable than historic mortars and can cause moisture to be trapped inside the masonry, leading to decay and other forms of deterioration. The susceptibility of mortar to decay agents has been found to depend on the type of masonry, its location, the micro-climatic condition and the composition, texture, mechanical and micro-structural characteristics of the mortar.

In an experimental evaluation of stone masonry walls with lime-based mortar under vertical loads, failure was seen in all the walls considered in an experimental study [5]. Mortar was observed to be squeezed, and stone blocks failed due to splitting tension.

Commencing the chronological trajectory with B. K. Jindal's seminal work in 1965[6], the study delved into the influence of surkhi fineness on masonry strength. In 1998, the viability of shotcrete as a fortifying agent for historic rubble stone masonry walls was investigated, discerning augmented water vapour permeability and reduced porosity as salient outcomes [7]. After almost ten years, in 2007, the seismic comportment of a Romanesque Church dome was examined [8], contributing to the discourse on structural integrity. Later, an experimental study was performed [9] to study the shear strength of conventional rubble stone masonry walls, expounding on its mechanical performance. It was also found that mortar composition has an important influence on the shear strength. The compressive strength of lime mortars, integrating surkhi and kankar as pozzolanic agents, was studied [10]. The study notably revealed a significant 77% increase in strength for the former, particularly under controlled humidity conditions. Subsequently, an experimental study was conducted [11] to evaluate lime-based mortar-clad stone masonry walls. This culminated in identifying primary failure modes attributed to squeezing-induced splitting tension and subsequent compressive stone fracturing. A scholarly work was done by optimising Random Rubble Masonry (RRM) retaining wall design [12], intricately informed by comprehensive analyses encompassing compressive, flexural, and shear strength considerations. In 2020, the author examined ancient construction materials [13], comparing their pros and cons with modern practices, focusing on earth-based mortars and their clay mineralogy's effects. The study also discussed the use of brick-based mortar for strengthening walls and explored the significance of lime mortars in novel approaches for wall reinforcement. During the same period, a research study on the mechanical characterisation of eight rubble stone masonry walls from various structures of a Portuguese monument assessed their quality using the Masonry Quality Index (MQI) and the Italian Building Code Commentary (IBCC 2019) [14]. Quantitative criteria were proposed for rating mortar and stone quality in MQI, and correlations between mechanical properties obtained from IBCC 2019, MQI, and double flat-jack tests demonstrated the benefits of quality assessment in estimating masonry mechanical properties.

A numerical study elucidates the confinement pressure and interfacial bond behaviour governing the mechanical response of masonry walls [15]. The study assessed shear mechanical parameters of masonry samples, considering the effects of confinement pressure and bond behaviour at sample-plate interfaces on mechanical responses. An experimental study [16] assessed shear and compressive strength parameters for stone masonry assemblies in Eastern Canada, and valuable insights into the mechanical properties of unreinforced masonry walls used in heritage building construction were given. In antiquity preservation, non-destructive assessment of Roman rubble stone masonry structures illuminated structural dynamics and preservation imperatives through visual inspection and sonic pulse velocity tests, affording estimations of mechanical properties that substantiate informed preservation strategies [17]. The

restoration of Alamparai Fort, aided by Gur and Haritaki as additive agents, enabled its resilience against the Nivar cyclone in November 2020. This highlights the significance of analysing existing structures and choosing suitable binding additives to protect heritage sites. [18]. The research used non-destructive investigation methods to understand rubble stone masonry in Roman archaeological sites, particularly at Pompeii. The extensive data gathered through surveys and sonic pulse velocity tests provided valuable insights into the mechanical parameters of these ancient masonry structures, aiding in preservation efforts [19]. Another study assessed the seismic behaviour of double-leaf stone masonry piers through experiments and 3D finite element micro-modelling, offering a useful laboratory tool for modelling [20]. Additionally, an effective retrofit method, reinforced connected plaster, was experimentally confirmed to enhance in-plane cyclic response. The research study on masonry dome behaviours considers support conditions, thickness, and curve parameters to identify neutral hoops through graphical and numerical analysis. The results classified masonry domes into four types of behaviour based on variables, including single-masonry, double-masonry with a single neutral hoop, double-masonry with both compressive and tensile hoops and a single neutral hoop, and treble-masonry with two neutral hoops [21]. The non-destructive investigation [22] proved suitable for assessing the mechanical properties of heritage masonry structures, focusing on opus incertum rubble stone masonry at Pompeii. The extensive dataset, including sonic pulse velocity tests, allowed for robust estimations of the mechanical parameters essential for preservation efforts. The research investigated the compositional and textural properties of bedding mortars from the National Palace of Sintra, built over several centuries [23]. It established similar mortar compositions based on locally available materials but varied textural features according to use (interior/exterior), proposing distinct repair mortar formulations. The findings also suggested potential links between mortar characteristics and the monument's historical background, although further analysis is needed for definitive correlations with different construction periods.

The literature review concludes with an overview of research on masonry dome behaviours, assessing mortar quality in historic structures, and the compositional and textural properties of bedding mortars from historic sites. It stresses the need for further research to establish correlations between mortar characteristics and the historical context of monuments.

## 2. Material and Methods

### 2.1. Material Specifications

Fine aggregate river sand was used as fine aggregate. The specific gravity of sand was 2.63, and the fineness modulus of fineness was 2.52. Second material considered is Lime (Hydraulic lime). Mix design proportion considered as Lime: Surkhi: Sand= 1: 4: 15. Basalt stones: In rubble masonry cubes, basalt stones ranging from 5 to 30 cms were used. These basalt stones were acquired from a nearby site. These basalt stones occupy 65 to 70% of the total volume of the total proportion of cubes. Basalt stones used in the cube are shown in below figure 7(a).

- Quick Lime: Slaked lime was a binding material in rubble masonry. This quick lime is acquired from limestone mines in Rajasthan. This lime was slaked for seven days in water and used after its slaking. The slaking of lime is shown below in Figure 7(b).
- Surkhi: Surkhi means powdered broken brick. This surkhi is used as a pozzolanic material in a mortar. It imparts colour and plasticity to mortar.



- Sand: Sand is used to reduce the shrinkage of mortar. Fine river sand was used. This river sand had a fineness modulus of 2.5 to 2.8, and silt content should not be less than 5 to 6%.
- Carbon fibre reinforced polymer (CFRP): To avoid edge failure of the cube during compressive loading, carbon fibre-reinforced polymer of grade HM-30 (unidirectional) was used. Before its application, the matrix 20 solution as an adhesive was applied to the cube surface.
- Neoprene Rubber: For uniform distribution of load through the cube, neoprene rubber of 8mm thickness and 700x700mm size is placed on the top surface of the cube.

## 2.2. Experimental Work to Determine Material Properties:

### 2.2.1 Testing of Cube Specimens

As per the requirement for the experimental investigation, in-house fabrication for the moulds of cube specimens was carried out. The inside dimensions of the Mould Size = 600 x 600 x 600mm and Plate size = 700 x 700 x 20mm

### 2.2.2 Testing of Masonry core to evaluate Strength

This study examined three core samples as per IS: 456-2000 and IS 516 (Part 4). These standards provide guidelines for core testing to assess masonry quality. The cores were considered acceptable if their average strength met at least 85% of the required masonry strength, and no individual core had a strength below 75%. The study tested 16 cores for various properties, such as strength, water absorption, density, and specific gravity. These properties were compared with the percentage of basalt in the cores and the core's strength.



Fig. 2. (a)Core samples before and after capping, (b)Testing of core in CTM

The core's strength was calculated using methods specified in IS: 14858, and the results were expressed in  $N/mm^2$ . Additionally, a correction factor based on the length-to-diameter ratio of the core specimen after capping was applied, following IS 14858. The core's material composition included lime, surkhi, sand, and basalt, with the mix proportion following standards. The core specimens had a diameter of 50mm, and their average length was 60-80mm. Refer Figure 2(a) and 2(b) for details. A correction factor, represented as "F," was determined based on the length-to-diameter ratio ( $l/d$ ) of the core specimen after capping, using the equation  $F = 0.11N + 0.78$ , where "N" is the length/diameter ratio. This correction factor is used to adjust the cylinder strength, making it equivalent to the strength of a cylinder with a height/diameter ratio of 2. This adjusted cylinder strength is multiplied by 5/4 to estimate the concrete's equivalent cube strength.

The core material is composed of lime, surkhi, sand, and basalt, with a specific mix proportion of 1:4:15. The core specimens have a diameter of 50mm (with an in-situ diameter of 43mm) and vary in length from 60-80mm, with an average length of approximately 69.56mm. The result and analysis are summarised in Table 1.

Water absorption is determined by measuring the weight of cores after they've been soaked in water for 24 hours (saturated weight) and then dried in an oven for 24 hours at 100°C (dry weight). Water absorption is calculated based on these weights.

### 2.2.3 Test on Lime Mortar Cubes

In the present study, a compression test was done on lime mortar cubes to determine their strength on 7, 14 and 28 days, respectively. It is crucial to determine the strength of lime mortar as it governs the failure of rubble masonry used in the dome of the pagoda structure. For the determination of strength of lime mortar, 9 cubes of lime mortar having size 70mmx70mmx70mm with mix design as 1(lime): 4 (surkhi): 15(sand) is casted and tested for 7, 14 and 28 days respectively. Water to lime plus surkhi ratio is taken as 0.63.

The detailed test procedure for casting and testing lime mortar cubes is as follows:

- Lime slaking: Lime was slaked in water for seven days.
- Batching of materials: The materials were batched according to the mix design, which was 1:4:15 (Lime: Surkhi: Sand).
- Calculating lime density: The density of lime putty was calculated by measuring the weight of an empty vessel ( $w_1$ ) and the weight of the vessel filled with lime putty ( $w_2$ ). The density of lime putty was determined using a table from IS 712-1964.
- Mixing: Lime putty was added to a mixer and stirred to remove air bubbles. Dry surkhi was added, and the mixture was stirred for 5 to 7 minutes. Water was added as needed to make the mixture homogeneous. Finally, sand was added, and the mixer was operated until the mixture was properly homogeneous. (Figure 3 (a))



Fig. 3. (a) Mortar mixer, (b) curing of Lime mortar cube, and (c) UTM for compression test

- Casting: In three layers, the lime mortar mixture was poured into properly oiled moulds of size 70x70x70mm.
- Compaction: Vibratory compaction was performed to ensure the mixture was well-compacted.
- Demolding: Molds were de-moulded after the mixture attained sufficient strength to retain its shape.
- Curing: Lime mortar cubes were wrapped in gunny bags (Figure 3(b)) from all eight faces and cured for 7, 14, and 28 days by sprinkling water on the gunny bags.

- Water absorption measurement: On the day of casting, the dry weight of the cubes was measured. The water absorption of the cubes was calculated by subtracting their dry weight from their saturated weight.
- These cubes were then tested in the universal testing machine (UTM) (Figure 3 (c)) for compression,
- and results were noted down

#### 2.2.4 Test on Rubble Masonry Cube

This experimental work aims to assess the compressive stress experienced by the rubble masonry and its associated structural properties, including the modulus of elasticity (E) and Poisson's ratio ( $\mu$ ).

This study evaluated the maximum compressive stress on rubble masonry and its modulus of elasticity (E) and Poisson's ratio ( $\mu$ ). A rubble masonry cube of 600x600x600mm was tested in a compression testing machine of 400 tonnes capacity. Using dial gauges and linearly variable differential transformer (LVDT), lateral and longitudinal strains were calculated to determine the modulus of elasticity and Poisson's ratio. The results obtained from these dial gauges and LVDTs were compared with compressive stress coming on rubble masonry. Comparison and test results are discussed below.



Fig 4. (a) Lime mortar, (b) Preparation of rubble masonry, and (c) final prepared rubble masonry cube

A specially fabricated 600x600x600mm test mould for rubble masonry was constructed, featuring a 20mm thick base plate and a 700x700mm height. An angle section was added at the corner to create a square cage, offering support and defining the mould's size boundary (See Fig 4©). Compression testing machine (CTM) with hydraulic lifting mechanism: A compression testing machine of 400 tones capacity was used to apply load on rubble masonry. Lime mortar preparation and arranging rubble masonry in layers can be seen in Fig 4(a) and Fig 4(b) respectively.

##### a. Preparation of rubble masonry cube

To prepare three rubble masonry cubes of size (600x600x600mm), same as above, three moulds of cubes with wooden shuttering were designed (Figure 5(a, b)). Wooden shuttering helps with the smooth finishing of rubble masonry cubes with mortar. It also allows for the confinement of the mould. Wooden shuttering of mould is shown in Figure 5(a). Casting of the cube is done in 2 phases. In 1<sup>st</sup> phase, 50% casting of 3 cubes is done. i.e., up to a height of 300mm. In 2<sup>nd</sup> phase, on the next day, the remaining casting is done.



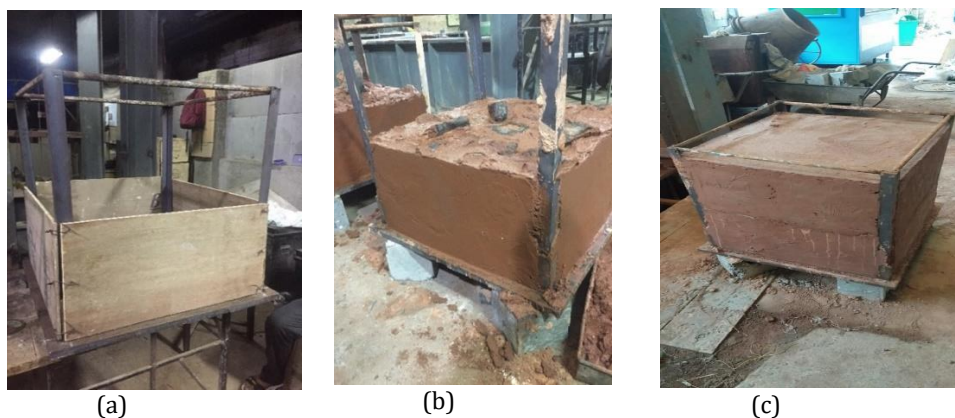


Fig. 5. (a) Wooden shuttering of mould, (b) 1<sup>st</sup> phase casting of cube, and (c) final rubble masonry cube after phase 2

For casting, mortar volume was considered 30% of the total volume of 3 molds. The remaining 70 % of the volume was occupied by basalt stone sizes ranging from 5cms to 30cms, see Fig. 5(b). Rubble masonry cube was cast in 2 phases. In 1<sup>st</sup> phase, 50% of casting up to a height of 300mm was done, as shown in the figure. During casting, initially, a layer of lime mortar was placed at the bottom of the mould. Stones of sizes ranging from from 5cms to 30cms were used. A skilled mason did the placing of stones with experience in this field. All the gaps between these stones were filled by prepared lime mortar. The workability of mortar should be such that it should fill all the voids between stones. The same procedure was repeated as above for 2<sup>nd</sup> phase of casting(Fig 5(c)), which should be done on the 2<sup>nd</sup> day of 1<sup>st</sup> phase. After the construction of both phases, wooden shuttering was removed and kept from curing, as shown in the figure below. The curing of the cube was done by sprinkling water regularly.

#### *b. Preparation of lime mortar*

Thirty Percent of the total volume of mould is taken as lime mortar. i.e., around 0.1944 m<sup>3</sup>. Mortar is prepared with a mix design 1:4:15 (Lime: Surkhi: Sand). From the mix design, the quantity of lime is calculated, and it is slaked in water for seven days before the day of casting. The density of lime is calculated by a 300 ml glass in gm/ml. The yield of lime is obtained using IS 712 from the density of lime. Multiplying this yield with the quantity of lime slaked in water gives a total amount of lime in liters used for mixing. First, lime and surkhi are added to the mixer. After 5-7 min of mixing, sand was added to a mixer. An adequate quantity of water is added for a homogeneous mortar mixture during the mixing.

The test procedure involved several steps: The compression testing machine (CTM) had the least count of 0.1 tonnes and used a hydraulic jack for load application, connected to a load cell, with the load cell's data sent to an indicator. A dial gauge with a 0.01mm least count measured the upward displacement of the base plate during force application. Six LVDTs with a least count of  $1 \times 10^{-4}$  cm were used to measure lateral and longitudinal deflection at various locations connected to a data acquisition system. Lime mortar was prepared in a transit mixer following a specific procedure. The cube was constructed by placing layers of lime mortar and stones, with lime mortar layers at the top and bottom. Curing was done by wrapping gunny bags and sprinkling water. Carbon fibre-reinforced polymer (CFRP) was applied to avoid edge failure, and the cube was placed on the CTM for testing. LVDTs and dial gauges were connected for data acquisition and calibrated, and then the load was gradually applied until failure, with deformations recorded.

### 3. Results and discussions:

#### 3.1 Evaluation of Masonry Strength Using Core Testing:

Table 1 indicates the percentage of basalt and respective core strength, water absorption, density and porosity and specific gravity of the core sample. It also indicates that failure is through mortar or basalt.

Test on the core sample shows that increased water absorption percentage decreases core strength. The strength of 95 MPa at 0.65% water absorption reduces to almost 5 MPa with 3.50% water absorption.

- Density of Cores: Core density is calculated by dividing the dry weight of the core by its volume, taking into account the uncapped length. Density is an important parameter for core analysis.
- Porosity of Cores: Porosity is determined by weighing the dry core and then saturating it with either water or air. The fluid weight in the pore space is calculated from the difference between the saturated and dry weights. The pore volume is obtained by dividing this number by the density of the saturated fluid. Table 1 shows that as the percentage of basalt increases, porosity decreases.
- Specific Gravity of Cores: Specific gravity is calculated by dividing the core's density by the density of water. The analysis shows that specific gravity remains relatively constant regardless of the percentage of basalt.

In terms of core failure patterns, the samples primarily fail at the interface between the lime surkhi mortar and the basalt components, often in a shear failure pattern. Shear failure occurs when forces applied to the materials cause them to slide along the interface, resulting in material cracks. The comparison between core test values and the analysis-design report values is provided in Table 2, offering insights into how the core test results align with the expected values outlined in the design report.

Table 1. Test results of core samples with various strength parameters

Sr. No.	Percentage Of basalt	Core Strength (MPa)	Water Absorption %	Density	Porosity	Specific Gravity	Failure through
1	12.28	5.13	3.50	2.48	7.32	2.26	Mortar
2	25.08	6.23	2.58	2.05	5.30	2.17	Mortar
3	29.02	10.36	2.82	2.22	6.26	2.37	Mortar
4	35.47	22.89	2.20	2.11	4.65	2.22	Mortar
5	38.35	22.10	3.40	1.93	5.49	2.11	Mortar
6	41.39	22.84	3.70	1.97	5.30	2.13	Mortar
7	45.02	18.70	2.84	2.31	6.56	2.47	Mortar
8	62.53	53.57	2.51	2.38	5.99	2.54	Basalt
9	63.54	40.24	2.14	2.48	5.30	2.62	Mortar
10	69.35	68.15	1.82	2.65	4.83	2.80	Basalt
11	70.47	62.00	1.83	2.61	4.78	2.74	Basalt
12	72.16	85.85	2.62	2.50	3.53	2.67	Basalt
13	72.70	87.91	1.40	2.51	3.50	2.60	Basalt
14	74.52	101.55	1.44	2.73	3.94	2.83	Basalt
15	75.67	65.20	1.71	2.93	2.99	3.07	Basalt
16	94.98	92.94	0.65	3.01	1.977	3.07	Basalt

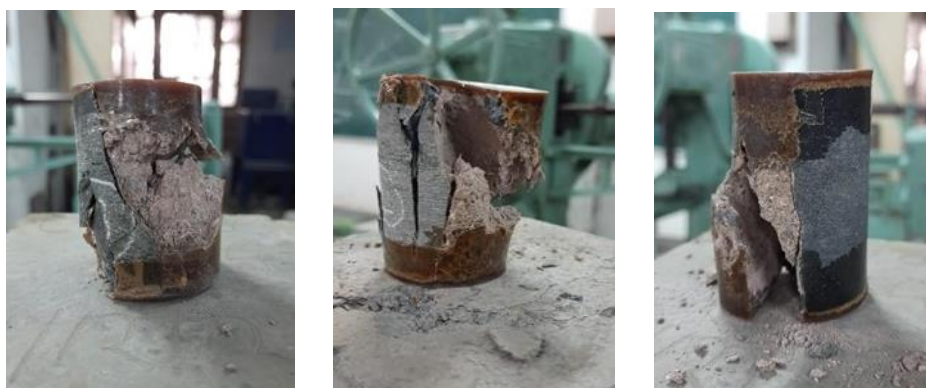


Fig. 6. Failure patterns of core samples

The failure pattern (Fig. 6) of the samples is predominantly at the interface between the lime surkhi mortar and the basalt components. This type of failure pattern is called a "core cut failure," which arises when a core sample is extracted from a masonry structure to evaluate its strength characteristics. In this context, the interface between the lime surkhi mortar and the basalt is critical in determining the structural integrity. Failure can be a shear, tensile, compressive, and debonding failure. However, the failure pattern is attributed to shear failure in the test scenario under consideration. Shear failure occurs when the forces applied to the materials cause them to slide against each other along the interface, resulting in cracks in the material. Comparison between core test values and analysis–design report values are given in Table 2.

Table 2. Comparison of strength parameters

Parameters	Core test values		Analysis & design report values (IIT, Bombay)
	Min.	Avg.	
Strength (MPa)	1.677	36.59	1.42
Density (kN/m <sup>3</sup> )	18.96	23.85	24
Water absorption (%)	4.396 (Max)	2.384	5

### 3.2 Result of Test on Lime mortar

Nine cubes underwent testing, with each set of three cubes subjected to compression tests at 7, 14, and 28 days, respectively, using a Universal Testing Machine (UTM) as depicted in Figure 3(c). The corresponding compressive strength results for these durations are provided in Table 3, and a visual representation is presented in Figure 7. A notable trend is observed in the compressive strength, indicating a 54.025% increase from 7 to 14 days and a further 57.09% increase from 14 to 28 days. This suggests a linear increase in strength with the extension of curing time up to 28 days, as illustrated in Figure 7.

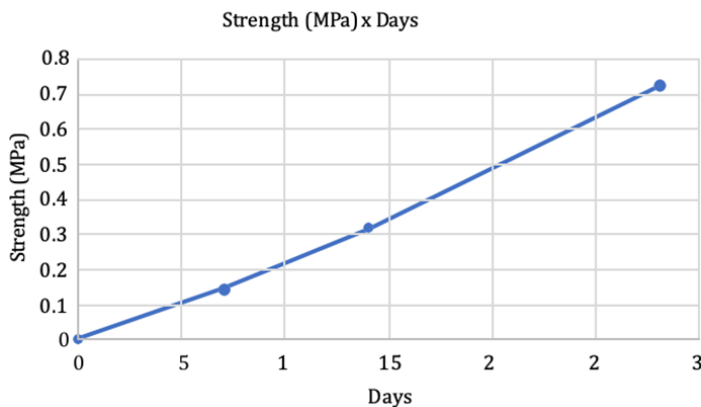


Fig. 7. Strength (MPa) vs days (Curing)

Table 3. Test results of 7-, 14- and 28-days compressive strength

7 days of compressive strength						
Sample	Saturated wt(gm)	Dry wt(gm)	Load (N)	Strength (N/mm <sup>2</sup> )	%Water absorption	Strength (Mpa)
1	712	614	736	0.15	15.96	0.15
2	706	610	706	0.14	15.73	0.14
3	710	619	686	0.14	14.70	0.14
Average value				0.14	15.46	0.14
14 days compressive strength						
1	711.50	617	1520	0.31	15.31	0.31
2	705.50	607	1569	0.32	16.22	0.32
3	719.50	605	1539	0.31	18.92	0.31
Average value				0.31	16.82	0.31
28 days compressive strength						
1	692	641	3726	0.76	7.95	0.76
2	704	629.50	3432	0.70	11.83	0.70
3	724.50	654	3628	0.74	10.77	0.74
Average value				0.73	10.19	0.73

### 3.3 Test Results on Rubble masonry

Batching was done according to the mix design 1:4:15 (Lime: Surkhi: Sand). Taking 35% of the total volume as lime mortar, it turns out to be 0.0756 m<sup>3</sup>. Lime quantity was 7.98 kg, surkhi was 31.95, and sand was 119.7 kg. The reason for selecting these proportions lies in achieving the desired characteristics of the mortar, such as strength, workability, and durability. Lime contributes to binding, while surkhi and sand provide filler and aggregate. The specific proportions aim to optimise these factors for the intended application.

After applying load in CTM, the cube failed at 38 tonnes, equivalent to 1.034 Mpa. Failure of the cube is shown in Figure 8. The reason for this failure can be attributed to factors like the composition and quality of the materials used in the cube's construction, the curing

conditions, and the structural integrity of the cube itself. The cube's breaking load and its conversion to stress provide valuable insights into its compressive strength, which is a critical parameter in assessing the performance of masonry materials and structures under load-bearing conditions.



Fig 8 Failure of cube

Calculation of modulus of elasticity (E) and Poisson's ratio ( $\mu$ ) According to ASTM C 469,

- The modulus of elasticity (E) is the ratio of normal stress to the corresponding strain for compressive stresses below the proportional limit of concrete.
- Poisson's ratio ( $\mu$ ) is lateral to longitudinal strain for related compressive stress.
- The modulus of elasticity and Poisson's ratio values are applicable within the customary elastic range (0 to 40 % of ultimate load).

A summary of test results from LVDT is given in Table 5.

Table 5. Overview of test results

LVDT	Position	Avg. Strain	Modulus of elasticity	Poisson's ratio ( $\mu$ )	
			(E) (MPa)	S3	S6
S1	Back	0.00040	517.38	0.25	0.24
S2	Front	0.00042	480.15	0.22	0.22
S3	Right- Lateral	0.00011			
S4	Right	0.00044	454.19	0.21	0.21
S5	Left	0.00042	482.45	0.22	0.26
S6	Front- Lateral	0.00011			
Average			E=483.54	$\mu=0.22$	$\mu=0.23$

From the stress vs strain graph as shown in Fig.9 (a-d), it is observed that for all the strain gauges, nonlinear behaviour is observed till the visible peak point of strain value of 0.0026 at 0.87MPa and after that, strain continuously increases from 0.0026 to 0.012 with an increase in strength from 0.87MPa to 1.03MPa. Later behaviour resembles linear behaviour. From LVDT readings, the average modulus of elasticity(E) is 458.4427109 Mpa, and the Poisson's ratio( $\mu$ ) is 0.211.



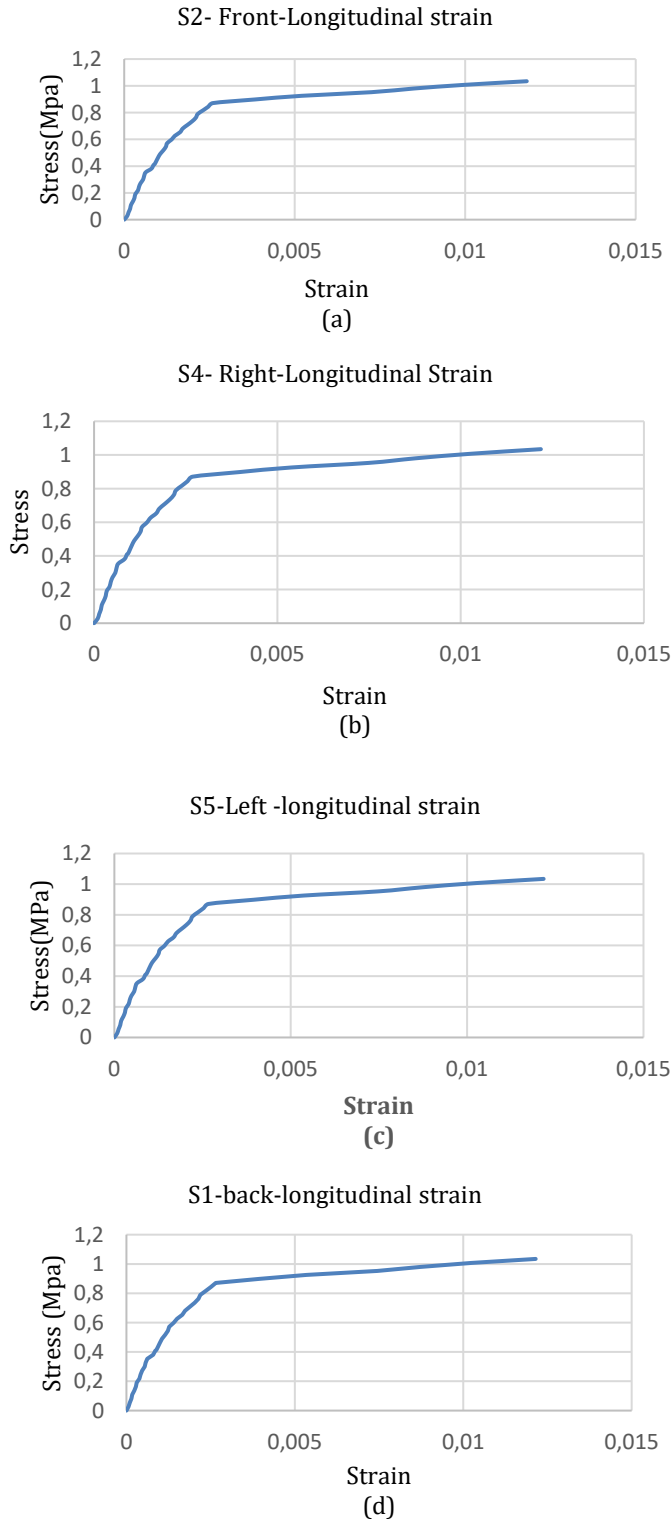


Fig. 9. Stress vs strain (a), (b), (c) and (d)

From the failure of the cube, it is observed that mortar strength is the governing factor for the strength of rubble masonry, as the failure strength of rubble masonry cube closely resembles the strength of lime mortar cubes. (1 MPa).

The stress-strain graph of rubble masonry exhibits a distinctive pattern: initially, the graph follows a parabolic shape, signifying a nonlinear stress response. As the strain increases, the curve transitions into a more linear trajectory. This behaviour suggests that at lower stress levels, the material undergoes deformation with a nonlinear relationship between stress and strain. However, as the stress increases, the response becomes more consistent and linear, indicating a more predictable deformation pattern. This observation shows the complex mechanical behaviour of rubble masonry, highlighting the need to consider its nonlinear and linear aspects for accurate structural analysis and design. From LVDT readings, we can conclude that the average modulus of elasticity (E) is 483.54 MPa, and the Poisson's ratio ( $\mu$ ) is 0.225 (Refer Table 5). This modulus of elasticity signifies the material's ability to deform elastically under an

applied load and return to its original shape once removed. A higher modulus of elasticity indicates a stiffer material that undergoes minimal deformation. A Poisson's ratio of 0.225 suggests that the material experiences a relatively small lateral expansion when subjected to axial compression or tension. This value aids in understanding the material's deformation behaviour and is crucial for accurate structural analyses and design considerations. From the failure of the cube, it is observed that mortar strength will govern the strength of rubble masonry, as the failure strength of rubble masonry cube closely resembles the strength of lime mortar cubes. (1 MPa).

This finding underscores mortar's critical role in determining rubble masonry's overall load-bearing capacity and structural integrity. While other factors, such as the arrangement of stones and the interlocking mechanism between them, undoubtedly contribute to the masonry's strength, the mortar's bonding capacity emerges as a primary factor. The failure pattern and load-carrying ability of the masonry largely depend on the adhesion and cohesion properties of the mortar.

#### 4. Conclusion

This experimental investigation into core samples from the Pagoda in Borivali, Mumbai, has provided valuable insights into the properties of the rubble masonry used in this heritage structure. The calculation of the percentage of basalt in the core samples revealed a positive correlation between the presence of basalt and the strength of the core, indicating that a higher basalt content contributes to increased strength.

Additionally, the study found that water absorption is a crucial factor affecting the strength of the core samples, with higher water absorption leading to reduced strength. The density of the cores was determined, considering the uncapped length, and porosity measurements showed that as the percentage of basalt in the samples increased, porosity decreased. Finally, the specific gravity of the cores remained relatively constant across different basalt proportions. These findings provide valuable information for the preservation and structural assessment of the Pagoda and similar heritage structures that utilize rubble masonry.

In addition to the findings, it is crucial to note that the predominant failure pattern observed in the core samples is the "core cut failure." This type of failure occurs at the interface between the lime surkhi mortar and the basalt components and is common when core samples are extracted from masonry structures for strength evaluation. The interface between these two materials plays a critical role in determining the structural integrity of the core samples. Failure modes, such as shear, tensile, compressive, and debonding, are

typically considered in structural assessments. However, in the specific test scenario under consideration, shear failure emerged as the predominant mode. Shear failure occurs when the applied forces cause the materials to slide against each other along the interface, leading to the development of cracks in the material. Understanding this failure pattern is essential for assessing the structural behavior and durability of rubble masonry in heritage structures like the Pagoda in Borivali, Mumbai, and can inform strategies for its preservation and maintenance.

Additionally, it is important to highlight that a total of nine cubes underwent testing. The data reveals a noteworthy trend in the compressive strength of the cubes over time. Between the 7-day and 14-day curing periods, there was a substantial 54.025% increase in strength, and from the 14-day to the 28-day duration and there was an impressive 57.09% increase in strength is observed. These findings emphasize the importance of considering the curing period when evaluating the compressive strength of the core samples, as it has a significant impact on structural performance.

In conclusion, the experimental investigation of rubble masonry used in heritage structures, such as the Global Vipassana Pagoda in Borivali, Mumbai, India, was conducted. This type of rubble masonry serves a crucial role in transferring the load on the dome of the Pagoda from the superstructure to its foundation. Given the dome's shell-like structure, the forces acting on this rubble masonry are primarily compressive. As part of this experimental program, the compressive stress on the rubble masonry was evaluated, along with its structural properties, including the modulus of elasticity (E) and Poisson's ratio ( $\mu$ ).

From the above experimental study, it can be concluded that it is possible to create heritage structures using rubble masonry with Lime surkhi mortar even today. Global Pagoda Vipassana in Mumbai, India, represents an excellent example. Preserving heritage structures is crucial, with rubble masonry playing a key role in this effort. As a traditional wall construction material in India, rubble masonry has stood the test of time, both in ancient and contemporary times, contributing to heritage structures. A combination of rubble masonry with additives like lime mortar and surkhi is essential to ensure structural longevity. This study uses rubble masonry, lime mortar, and surkhi to repair and construct heritage structures, serving as an eco-friendly alternative to conventional cement mortar. The case study of the Global Vipassana Pagoda in Mumbai exemplifies this approach. By analysing stress-strain graphs, LVDT readings, and cube failure patterns, it's evident that the material properties and composition, especially mortar strength, greatly influence the structural integrity and load-bearing capacity of rubble masonry. This experimental study offers insights into designing and preserving heritage structures using the time-tested technique of rubble masonry with lime mortar and Surkhi.

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