Comparative evaluation of properties of laboratory test specimens for masonry mortars prepared using different compaction methods

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Abstract. Development of new solutions for masonry mortars is heavily reliant on laboratory-based experimental procedures. This study provides insights into the properties of masonry mortars, prepared by four distinct compaction methods, based on existing standards: tamping, tapping, jolting and vibrating. The particular mortar mix under study has been designed in volumetric proportions of 1:1:6 with air lime, cement and sand, respectively. Evaluation of differences among compaction methods is based on bulk density, mechanical strength, porosity and water absorption measurements at 7 and 28 days. Density and strength testing results indicate statistically significant differences, where mechanically compacted mortars are denser and stronger than their manually compacted counterparts. Similar development is observed through assessment of mortar porosity. The variation is noticeable in gel and capillary pore range as shown by mercury intrusion, while open porosity evaluated by vacuum immersion also indicates some distinction between manual and mechanical compaction, with the latter producing less porous mortars. On the other hand, capillary water absorption results reveal higher coefficients for jolted and vibrated samples, hinting at different pore interconnectivity in mechanically and manually compacted mortar specimens.

Keywords: Lime-based mortar, compaction methods, fresh properties, hardened properties, analysis of variation.

1 Introduction

Even though masonry construction has been paramount to humankind since around 8000 years ago, it still remains a crucial field for new developments and preservation of historic structures [1]. In both cases masonry is often composed of building blocks connected together by mortars, where lime-based materials have been and still are of primary importance [2, 3].

Robust experimental methods are needed to ensure that laboratory-developed lime-based products are representative of real-life structures. In the case of masonry mortar preparation in the laboratory, a specimen of 160x40x40 mm³ is considered a standard mortar prism for strength testing, and this property is the only requirement based on Eurocode 6 [4]. However, there are more properties of a masonry mortar impacted by the compaction of the prismatic mortar specimens. Current standard for masonry mortars EN 1015-11 [5] describes two manual compaction procedures: the first involves compaction of the mortar by stroking it with a tamper, while the alternative suggests tilting the mould at a 30° angle and tapping it on the table. Even though these manual compaction methods are prescribed in the masonry mortar-specific standard, researchers sometimes [6, 7, 8, 9] opt for machine-compaction similar to what is described in cement-specific standard EN 196-1 [10]. This standard also presents two compaction methods: the former involves compacting the mortar on a jolting table, while the latter suggests using a vibrating table. Inevitably, due to the nature of these compaction procedures, they introduce different levels of compaction energy into the mortar mixes, thus affecting properties such as hardened density, porosity, mechanical strength, water absorption capacity and susceptibility to potentially harmful substances. All these properties are important not only in characterizing laboratory-produced mortars, but also with regards to their real service life in modern masonry construction and conservation and repair of historic structures.

This study describes an experimental campaign designed to compare the four different mortar compaction methods mentioned above. Lime-cement mortar mixes are cast in prismatic moulds, compacted and cured for 7 and 28 days to evaluate the time-dependent change of properties. At the respective ages, differently compacted mortars are measured and weighted, allowing the calculation of their density. Various tests are performed, including mechanical strength, water absorption by capillarity and mercury intrusion porosimetry supplemented by open porosity test to evaluate the broader range of pore sizes. This setup could allow drawing conclusions not only regarding how different compaction methods fare in comparison with one another, but also which is the most representative compared to real-life masonry applications in new building, repair and conservation. However, the curing times used in this study are insufficient to assess any developments in mortar properties arising from the carbonation of air lime.

2 Materials and methods

2.1 Mortar mix and preparation

A mix of 1:1:6 parts by volume of air lime, cement and sand was selected as the main mortar composition for this study. Lime is high-calcium hydrated lime CL90S, conforming to the requirements of EN 459-1 [11], provided by Lhoist [12]. It was paired with limestone cement CEM II / A-L 32,5 R as specified in EN 197-1 [13], supplied by Tarmac [14]. CEN standard sand, based on EN 196-1 [10], was chosen wittingly to limit the variability of aggregates when preparing different mortar batches. In addition to dry components, regular tap water was used; the amount was adjusted to achieve mortar consistency of 175±10 mm flow table value as specified in EN 1015-11 [5]. Exact quantities, based on bulk densities of the above-mentioned materials, are presented in Table 1 below.

Table 1. Composition of lime-cement mortar.

Lime: Cement: Sand (by volume)	Lime (g)	Cement (g)	Sand (g)	Water (g)	w/b ratio (by mass)	w/b ratio (by volume)	Flow table value (mm)
1:1:6	57	141	1350	208	1.05	0.765	170 (±4)

2.2 Compaction methods

Manual compaction

- Tamping

Based on masonry-specific standard EN 1015-11 [5], the process of tamping involves stroking fresh mortar layers 25 times using a tamper rod. Compaction is achieved through impact loading, which is highly dependent on the operator.

In practice, compaction by tamping was performed by the same operator for all mortar batches, minimizing potential differences in tamper strokes. The tamper rod was a metal cylinder with a diameter of 20 mm. Extra detail was devoted to covering the full area of fresh mortar layer to limit the unevenness and formation of possible air pockets. This was practically achieved by consistently alternating strokes from one side of the imaginary centreline to the other, along the length of the prismatic mould while counting the strokes.

- Tapping

Proposed as an alternative to tamping, the action of tapping requires no extra tools. Fresh mortar layers are compacted by tilting the mould at an angle of approximately 30° and tapping it on the working surface (i.e. table or bench) 10 times.

Based on experience, successful execution of this method required tilting and tapping both sides of the mould alternately. Similarly, a simple guide marking the 30° angle was made to perform compaction in a more controlled pattern. The working surface was a wooden laboratory bench and the time required to complete compaction was approximately 30 seconds.

Mechanical compaction

- Jolting

Contrary to EN 1015-11 [5], cement-specific standard EN 196-1 [10] proposes the use of mechanical compaction methods for cement-based laboratory mortars, still applied in the case of masonry, as mentioned previously. Of these compaction methods, jolting is most common, making use of a jolting table – a mechanical apparatus which secures the mould and shakes every mortar layer for a total of 60 times, one every second. This procedure is automated and the apparatus exerts the same force with every jolt.

- Vibrating

Another way of compacting fresh masonry mortar mechanically is by means of a vibrating table. In contrast to jolting, a vibrating table operates at a constant frequency with the mould placed on top for a total of 120 seconds. The operation starts immediately after filling the first mortar layer, while the second is added after 60 seconds.
The vibrating table used in this study was a portable vibrating table from Testing [15]. The technical specifications and geometry were different from those described in EN 196-1 [10].

2.3 Curing conditions

After preparation, mortars were immediately placed into curing chamber with relative humidity at 95±5% and temperature of 20±2°C [5]. Demoulding was performed at 2 days and the mortars were kept in the same conditions for 5 more days. After a week, mortars were either tested for respective properties, or transferred to 60% relative humidity and 20°C room until the age of 28 days.

2.4 Mortar properties

Density

Densities of mortar prisms were obtained at 7 and 28 days. The actual dimensions of prisms were measured with a Vernier scale, allowing calculation of volume; mass was measured on a laboratory balance (0.05 g precision). Division of mass by the calculated volume resulted in bulk densities of mortar samples. A total of 6 samples were prepared for density evaluation on two separate occasions.

Mechanical strength

Flexural and compressive strengths were measured at 7 and 28 days with a walter+bai combined testing machine [16], following EN 196-1 [10] standard loading protocol. A total of 6 samples were prepared for strength testing on two separate occasions.

Porosity

Mercury intrusion porosimetry (MIP) is a non-standardized, yet widely applied method to evaluate pore volume, size and distribution in a mortar matrix [17, 18, 19]. For this experimental campaign, the samples for MIP were extracted from the intact mortar prism pieces, remaining after mechanical testing. Only mortars aged for 28 days had sufficient structural stability to extract the samples, indicating an adequately developed microstructure for pore detection. The microstructure was preserved by solvent-exchange method with isopropanol, designed to stop further hydration and carbonation of the samples [20, 21].

Method to measure porosity by immersion under vacuum, adopted from RILEM CPC 11.3 [22], was applied to estimate the total open porosity of mortar samples. However, the drying step was performed at the end of the experiment for the purpose of preserving the microstructure during testing. This test was chosen in order to complete the gel and capillary porosity by MIP with macro-porosity estimation. A total of 3 samples were prepared for the test.

Water absorption

Water absorption by capillarity was tested according to EN 1015-18 [23]. The number of measurement times was increased in order to produce a typical water absorption curve. A total of 3 samples were prepared for the test. To aid the expression of results, water absorption coefficients were computed using the following equation:

$$\boldsymbol{C} = \frac{M_{90} - M_{10}}{A\sqrt{t_{90} - t_{10}}} \tag{1}$$

Where:

M_{10} – absorbed water after 10 minutes, kg;
M_{90} – absorbed water after 90 minutes, kg;
A – area of the submerged face - 0.0016 m^2;
t_{10} – 10 minutes;
t_{90} – 90 minutes;
C – coefficient of water absorption, $kg/(m^2 min^{0.5})$.

Statistical analysis

To aid the comparison between compaction methods, statistical analysis of variance (ANOVA) was performed on results of density and strength (based on 6 mortar samples) as well as water absorption and open porosity (based on 3 samples). Statistically significant differences were further processed with Tukey’s honestly significant difference (HSD) test and where outliers were found and removed from the dataset by modified Thomson Tau test – with Tukey-Kramer test.

3 Results

3.1 Density

Bulk density is a useful property which aids the comparison of previously discussed compaction methods. Despite being the easiest parameter to calculate and assess, bulk density provides the first insights into the level of compaction attainable with different methods. It could help to indicate the variation of air voids and pores, hint at their size and predict the strength of mortars.

Recorded in Table 2, bulk density results at 7 days are based on calculations of average values from 6 mortar samples, prepared on two separate occasions for each method of compaction, further supplemented by the standard deviations and coefficients of variation. Based on the results, mechanically compacted samples have higher density than manually compacted ones, but the difference between jolting and vibrating is larger than that between tamping and tapping.

Table 2. Bulk densities of mortars at 7 days.

Compaction method	**Manual**		**Mechanical**	
	Tamping	Tapping	Jolting	Vibrating
Bulk density avg. (kg/m3)	2180.6	2168	2237.1	2216.1
Standard deviation (kg/m3)	36.6	29.4	17.5	39.4
COV (%)	1.7	1.4	0.8	1.8

Similarly, density results at 28 days are presented in Table 3. These values are based on different samples than those recorded in Table 2, but equivalently, the variability is assessed from 6 samples prepared on two different occasions per compaction method. As expected, bulk densities are lower than those at 7 days due to water evaporation, but the overall trend is still observed – both manual compaction methods produce similar results, while higher bulk densities are achieved by mechanical compaction methods. The difference between jolting and vibrating is more prominent as well.

Table 3. Bulk densities of mortars at 28 days.

Compaction method	**Manual**		**Mechanical**	
	Tamping	Tapping	Jolting	Vibrating
Bulk density avg. (kg/m3)	1980.6	1989.3	2027.4	2053.4
Standard deviation (kg/m3)	7.3	12.7	17.5	16.3
COV (%)	0.4	0.6	0.9	0.8

3.2 Mechanical strength

Strength is arguably the most important property of a masonry mortar, at least from quality control point of view (according to existing regulations), with compressive strength being the only elective parameter in Eurocode 6 [4]. However, the experimental procedure involves both flexural and compressive testing of a mortar specimen at the same time, therefore these results are paired together.

Results of compressive strength are displayed in Figure 1. At the age of 7 days, the strength ranges from 4.39 MPa to 5.21 MPa. When tested at 28 days, mortars show developed compressive strength of 7.25-8.4 MPa. Particularly striking in Figure 1 is the peaking compressive strength of vibrated specimens at 28 days. Such a result indicates that vibrational compaction is completely unmatched for the compressive strength, when even jolted samples yield results closer to manual compaction methods.

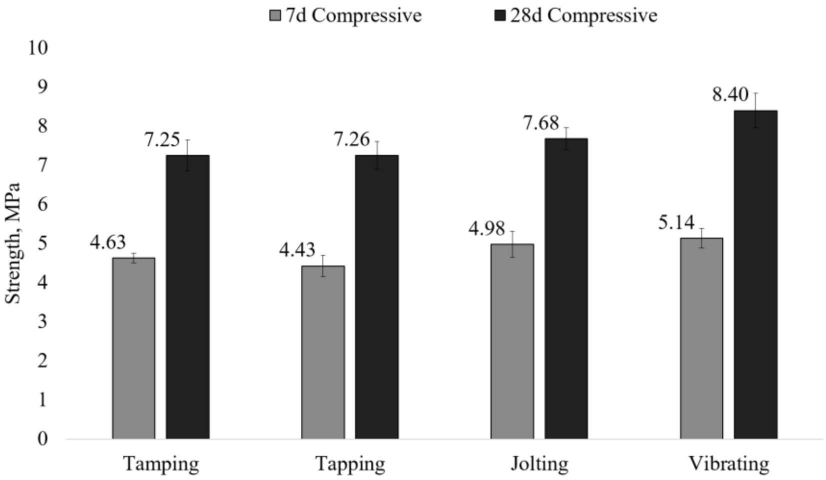

Figure 1. Compressive strength of mortars at 7 and 28 days of age.

As in the case of compressive strength and Figure 1, comparable trends can be observed in flexural strengths, where manual compaction methods produce samples with lower bending strengths than mechanical compaction methods. At the age of 7 days, as presented in Figure 2, lime-cement mortars have flexural strength in the range of 0.92-1.12 MPa and at 28 days in the range of 1.66-1.83 MPa. Manual compaction methods are more comparable to one another than mechanical methods, although the difference between the latter two is not as pronounced as previously observed for compressive strengths in Figure 1.

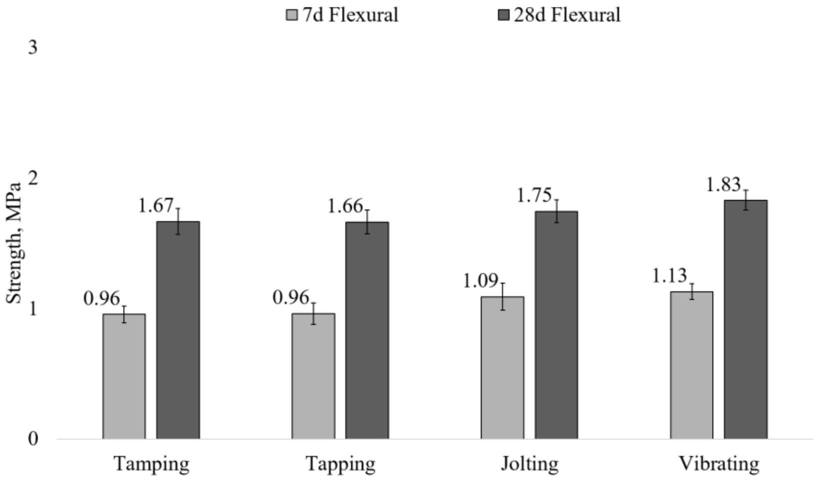

Figure 2. Flexural strength of mortars at 7 and 28 days of age.

Results in Figures 1 and 2 present standard deviation bars which are more noticeable when compared to standard deviation values in case of densities. Still, this variation is expected due to the destructive nature of the experiment and many different factors influencing the result.

Overall, mechanical strength values are within the range reported in literature for similar mortar mixes [7], with some sources reporting slightly lower values [6, 9], but these results would be considerably influenced by the choice of binder and aggregate materials and actual mix design quantities.

3.3 Porosity

Mercury intrusion porosimetry

Figure 3 presents the results of cumulative porosity as estimated based on the volume of intruded mercury. The graphs indicate rather insubstantial changes in the gel and capillary porosity for manually tamped and tapped, as well as mechanically jolted mortar samples. These compaction methods yield samples with porosity of ~18-19%. Notable difference is observed in vibrated samples, where the amount of both gel and capillary pores is considerably lower, with ~16% in estimated total porosity.

The results shown in Figure 3 indicate significantly lower porosity values by mercury intrusion than those reported in literature for 1:1:6 mortar mix designation [18].

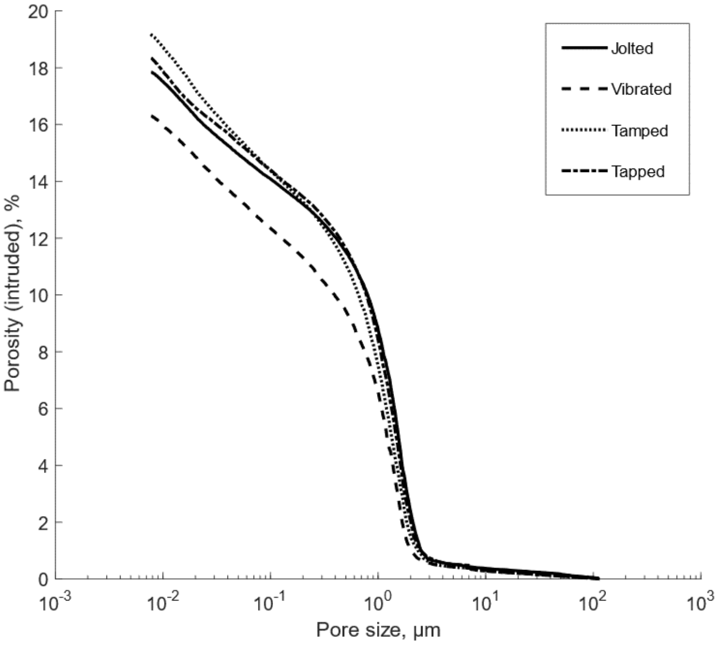

Figure 3. Cumulative intrusive porosity of differently compacted mortars at 28 days.

Porosity by immersion under vacuum

The results of open porosity in mortar samples are based on the percentage of water uptake under vacuum, as expressed in Figure 4. It reveals the slightly higher values of total porosity of manually compacted samples, compared to mechanical methods. However, between the latter, vibrated samples are showing larger average result as well as broader standard deviation than jolted ones.

Contrary to porosity evaluation by mercury intrusion, the open porosity results are closer to those achieved by other researchers [6, 18].

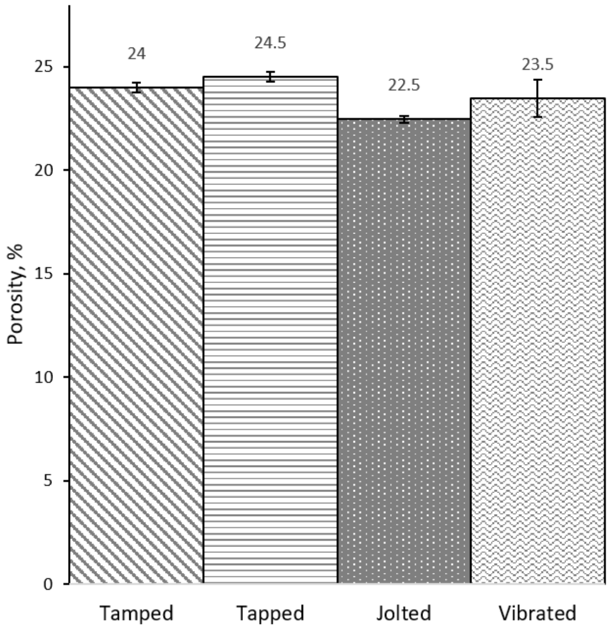

Figure 4. Open porosity of differently compacted mortars at 28 days.

3.4 Water absorption by capillarity

Water absorption of differently compacted mortar samples is presented in Figure 5 with the aid of curves, constructed from absorbed water mass measurements at 0, 1, 3, 5, 10, 30, 90, 180 and 1440 minutes. Furthermore, the water absorption coefficients, as specified in EN 1015-18 [23], are calculated based on Equation 1.

Unexpectedly, the results presented in Figure 5 suggest that mechanically compacted samples absorb more water more rapidly than manually compacted ones, despite having lower porosity. This is also confirmed by water absorption coefficients, where lowest values are produced by tamped samples, followed by tapped, vibrated and jolted specimens.

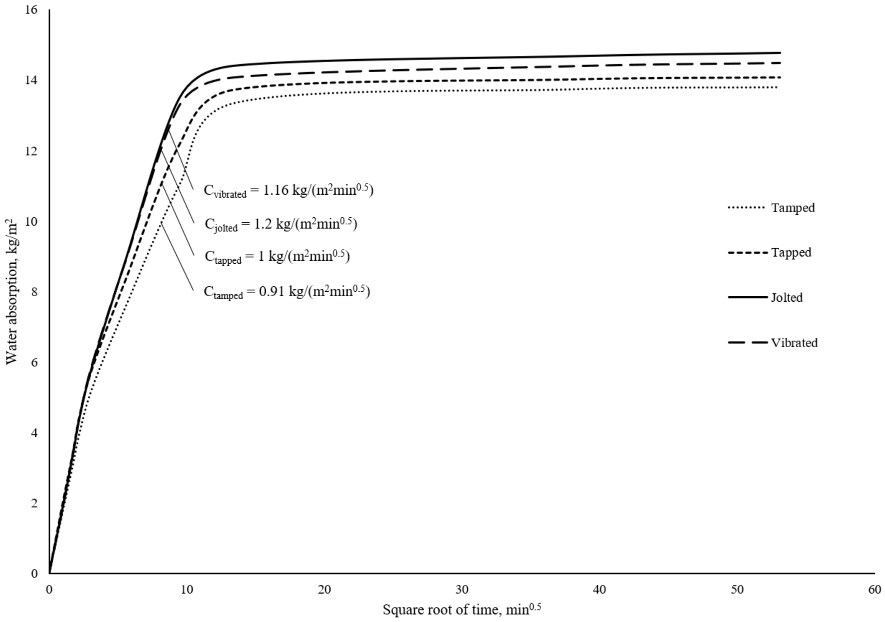

Figure 5. Water absorption of mortars at 28 days.

3.5 Statistical analysis

ANOVA results with Tukey-Kramer HSD are presented in Table 4 below. Generally, in all measured properties the differences between compaction methods were significant, with specific pair-wise differences highlighted in the table. Evidently, the results of tapping and tamping are not significantly different, contrary to all the manual-mechanical method pairs, where 5 out of 8 measured properties indicate significant difference. Comparison of jolting and vibration also demonstrates significantly different results for density and compressive strength measurements at 28 days.

Table 4. ANOVA with Tukey-Kramer HSD results.

		Density		**Compressive strength**		**Flexural strength**		**Porosity**	**Water absorption**
Age		7	28	7	28	7	28	28	28
Pair		Statistically significant difference found?							
Tamping	Tapping	No	No	No	No	No	No	No	No
Tamping	Jolting	Yes	Yes	No	No	Yes	No	Yes	Yes
Tamping	Vibration	No	Yes	Yes	Yes	Yes	Yes	No	No
Tapping	Jolting	Yes	Yes	Yes	No	Yes	No	Yes	No
Tapping	Vibration	No	Yes	Yes	Yes	Yes	Yes	No	No
Jolting	Vibration	No	Yes	No	Yes	No	No	No	No

4 Conclusion

This study presents a comparative analysis of laboratory-produced masonry mortars, compacted using four different methods, namely manual tamping and tapping and mechanical jolting and vibration, all of which are specified in masonry and cement-specific standards. It should be noted that while all discussed compaction methods are used in laboratory practice, the choice is rarely justified. Even so, if the topic of debate concerns controlled and repeatable laboratory mortar production, the results of the present study indicate no particular superiority or inferiority of any compaction method with regards to these aspects. Within the scope of this work, all methods have led to similar variations in measurements of specific properties. This was unanticipated in view of the less controlled nature of manual compaction.

On the other hand, analysis of mortar properties elucidates the distinction between manual and mechanical compaction. Lower results for density and strength of mortars compacted manually present an expected outcome of the hand-operated process, which remotely mimics the bricklaying construction. By contrast, mechanical compaction methods introduce significantly higher compaction energy into fresh mortar mixes, resulting in denser and stronger mortar specimens. Nonetheless, the results of open porosity evaluation also suggest better performance by the jolted and vibrated specimens, albeit the difference being not particularly convincing when compared with tamped and tapped samples. In relation to micro-porosity, the trend breaks as jolted mortars produce similar pore size distribution to manually compacted mortars, while vibrated stand out by showing lower amounts of gel and capillary pores. Counterintuitively, water absorption by capillarity reveal larger rates and capacities of less porous mechanically compacted samples, than of those compacted manually. Even though mostly statistically insignificant, such phenomenon is not easily explicable, hindering the correlation with other observations in mortar properties.

Additionally, a pronounced difference of compressive strength results attainable by jolting and vibration raises potential concern regarding the suggestion to use these mechanical compaction procedures as alternatives. Especially noteworthy in this sense are the similar results in mortars produced by manual tamping and tapping, rationalizing the notion to use them interchangeably. Pairing this fact with representative properties and acceptable variability among different mortar batches could suggest that manual compaction methods are more suited for laboratory-prepared masonry mortar specimens.

However, it is important to note that the choice is heavily dependent on the intended application. Unsurprisingly, masonry-specific compaction methods produce results which are more comparable to real-life masonry structures due to mostly manual nature of brick working. Likewise, enhanced mortar properties achievable by mechanical compaction are inherent to cement mortars, directly linked to concrete research. Since concrete requires compaction in most applications, this practice is likely reflected in laboratory setting with mortars. Although in this study mechanical compaction methods appear to be less comparable to one another and produce similar variability as manual methods, such outcomes have to be treated carefully. A note of caution is due here since there are multiple sources of potential error: availability and choice of equipment, operator-dependent inputs, machine-dependent faults, calibration, environmental conditions, quality and storage of raw materials are only a few considerations. The present study has laid grounds for further investigations, which could consider these factors along with the variable mortar composition and comparative evaluations based on field mortars.

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