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Mechanical Characterisation of Multi-wythe Quay Walls in Amsterdam

Uday Jain(✉) and Rita Esposito

Delft University of Technology, Delft, The Netherlands
{u.jain,r.esposito}@tudelft.nl

Abstract. Historical masonry quay walls in the inner city of Amsterdam need maintenance due to aging, and deterioration of foundations. These structures are not only critical to the transport infrastructure of the city, but also hold great heritage and monumental value being UNESCO World Heritage site. However, there is a notable lack of knowledge and documentation regarding the mechanical properties of these multi-wythe, unreinforced brick masonry walls, which poses challenges to the assessment of their structural safety.

This research investigates the mechanical properties of masonry for typical quay walls presenting the results of experiments for four different quay wall locations in Amsterdam. Masonry properties were determined via core testing due to its minimal invasiveness to the structure and its ability to adopt standard extraction and testing facilities. Companion tests on brick and mortar were performed to evaluate their compressive properties. Samples were obtained from both above and below the waterline to assess the effect of submersion on the mechanical properties. This study offers an insight into the mechanical properties of quay walls in Amsterdam, enhancing understanding of multi-wythe masonry and supporting the assessment and preservation of urban infrastructure in Dutch cities.

Keywords: Historical infrastructure · multi-wythe masonry · core testing · compressive properties

1 Introduction

The city of Amsterdam is home to an extensive network of historic masonry quay walls, many of which date back to 18th and 19th century. These structures are integral to the urban landscape - serving not only as functional infrastructure lining the city's canals but also as valuable cultural heritage embedded within the UNESCO-listed city centre (see Fig. 1) [1]. The municipality of Amsterdam is responsible for the assessment and maintenance of 600 kms of quay walls [2]. In recent years, however, growing concerns have emerged regarding their structural safety, driven by aging materials, foundation deterioration, and increasing urban loads due to modern traffic and utilities [3, 4]. In some cases, this has resulted in visible deformations and even partial collapses, highlighting the urgent need for effective maintenance and assessment strategies.

A significant portion of these quay walls consists of multi-wythe, unreinforced brick masonry, constructed with locally sourced materials and historic lime-based mortars.

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Fig. 1. A quay wall in Amsterdam

These quay wall cross-sections often exceed 600–1200 mm in their thickness and are fully bonded throughout. However, despite their structural and heritage importance, there is currently limited knowledge regarding their mechanical properties. This knowledge gap impedes appropriate structural assessment and limits the development and implementation of appropriate intervention strategies. The lack of mechanical data on quay wall masonry also limits the development of probabilistic methods that could help prioritise repairs or strengthening interventions based on risk or structural uncertainty.

The mechanical characterisation of historic masonry is inherently challenging. Full-sized extraction and standardised testing, such as wallet or prism compression tests, are typically infeasible due to access limitations, preservation concerns, and the scale of interventions required. To address these constraints, core testing of drilled cylindrical specimens has emerged as a minimally invasive technique, enabling compressive and shear testing on samples that include the full masonry assembly - brick units and mortar joints - within a small volume. Guidelines such as UIC 778-3 [5] and recent experimental studies [4, 6–12] have demonstrated the potential of this method, though they have largely focused on single- or double-wythe masonry. The application of core testing to multi-wythe urban infrastructure, with its inherent variability along length, thickness, and exposure to environmental conditions, remains underexplored.

This paper presents part of a broader research project aimed at developing a comprehensive material characterisation strategy for historic multi-wythe masonry infrastructure in Dutch cities. The focus of this paper is on compression testing of core samples extracted from quay walls in Amsterdam. Complementary tests on brick constituents were also performed. Samples were obtained from different locations within the wall - including areas above and below the waterline - to examine the effect of submersion on mechanical properties. By contributing new experimental data on the mechanical behaviour of Amsterdam's quay wall masonry, this study supports ongoing efforts to improve structural assessment and conservation of historical urban infrastructure.

2 Materials and Methods

2.1 Selected Quay Wall Case Studies

For this study, masonry cores from two quay walls, hereafter referred to as B2 and KBW, were considered. The cores were initially extracted to determine cross-sectional geometry, as the original construction details are often unknown. Later, it was decided to use them also to characterise the mechanical properties of masonry. Since the selection of drilling locations was primarily governed by site-specific constraints, accessibility, and ad-hoc project decisions, the available samples only allowed characterisation of the compressive response of brick and masonry. An effort was made to assess the mortar properties, but intact specimens suitable for double punch test could not be extracted.

The selected quay walls are made of multi-wythe unreinforced clay brick masonry. Archival data suggests the construction period to be between 1875 and1925. Bricks measured 200–220 mm (at B2) and 220–250 mm (at KBW) in length, with the height being 40–50 mm at both locations. Although core diameter limited direct measurement, a minimum brick thickness of 100 mm was observed at both locations. Compressive strength of bricks was evaluated using small 40-mm cubic specimens as suggested in previous studies [13, 14] and the normalised compressive strength was then determined using the shape factor of approximately 0.80 proposed in Table A.1 in EN 772-1:2011 [15] (Table 1). Historical sources indicate that mortar used in the construction of waterworks in the Netherlands, and in Amsterdam specifically, was characterised by the use of shell lime and trass [16, 17]. The possible proportion of these ingredients are discussed by Van Hees and Lubelli [18] and Van Balen et al. [19].

As environmental conditions may affect the mechanical response of masonry material, characterisation was performed considering possible variation along the height (above and below the waterline) and thickness (internal and external side) of the quay wall. Differences along the length of the quay wall (ca. 60m for KBW [20] and 8m for B2 [21]) could not be evaluated due to the limited number of samples. For KBW, it was found that above waterline portion was renovated using reinforced concrete; thus, only below-waterline masonry was evaluated. Core samples had a total length between 700–1400 mm but were typically extracted in 3–5 segments of 200–400 mm length each. The bond pattern at the core face was irregular, lacking well-defined joint configurations (e.g., T-, H-, or I-shaped) commonly used in literature [7, 9, 12]. On-site extraction and subsequent cutting of sample were performed using wet diamond drilling and sawing.

Table 1. Compressive strength of brick.

Location	No. of samples	Compressive strength		
		Mean (MPa)	Normalised (MPa)	CoV (%)
B2	8	19.77	16.02	17
KBW	5	15.36	12.44	36

2.2 Testing Set-Ups and Procedures

Uniaxial compression tests were conducted on horizontally-loaded cores to characterise the nonlinear behaviour of masonry. The samples, with 100-mm diameter, were cut along the thickness to obtain specimens without collar joints. The specimens had a thickness ranging between 70 and 110 mm. To ensure uniform load transfer, both ends of each specimen were capped using high strength mortar (Cuglaton Gietmortel 1 mm), which had a compressive strength of 50.55 ± 2.08 MPa and a flexural strength of 9.52 ± 1.56 MPa after 28 days of hardening. A custom side-formwork system was employed to cast both caps simultaneously (see Fig. 2a), in contrast to the sequential vertical casting used in earlier studies [11, 22, 23]. This modification streamlined the preparation process and reduced handling time. The cap had a length of 70 mm and a minimum height of 50 mm at the centre (see Fig. 2c). Capped specimens were demoulded after 3–5 days and tested after a minimum curing period of 14 days at ambient laboratory conditions, once the specimens had reached a constant mass.

A displacement-controlled hydraulic testing machine with a 3500 kN capacity was used for the compression tests. The test was conducted monotonically with a loading rate of 0.002 mm/s to capture the full nonlinear response, including post-peak behaviour. Four Linear Variable Differential Transformers (LVDTs) were used to record the deformation (Fig. 2c). Two vertical LVDTs were attached equidistant to the centreline of the core face to measure axial deformation. Two horizontal LVDTs were mounted orthogonally on the specimen with maximum length corresponding to the cap length. This ensured LVDTs remaining attached for a longer duration, enabling measurement of lateral deformation through the loading process. In addition, four LVDTs were mounted on the loading plates to monitor potential rotations, particularly during the initial stages of loading.

Mechanical properties were derived from the resulting stress-strain curves – an example is presented in Fig. 3. The normal stress was computed based on the cross-sectional area of cap. The axial strain was derived from LVDTs readings until peak and then from corrected jack displacement in the post-peak phase. The elastic modulus was calculated using the chord method between 1/10th and 1/3rd of peak stress, in accordance with previous studies [4, 23]. The fracture energy in compression was calculated as the area under the stress-strain curve considering an estimation of the ultimate strain ε_U (strain corresponding to zero stress). The estimation of the ultimate strain depended on the test duration relative to post-peak softening. For most specimens, the test continued until a drop in force of at least 70% of the peak force.

(a) (b) (c)

Fig. 2. Capping of masonry cores: (a) Formwork for pouring high-strength mortar for both caps simultaneously, (b) final specimen with the two caps, and (c) Overview of specimen geometry and LVDTs arrangement (similar at back side)

In this case, the ultimate strain was evaluated considering a linear extrapolation of the stress-strain curve between 50% and 70% drop in peak force ($0.5\,f'_m$ and $0.3\,f'_m$ respectively). For 7 out of 26 specimens tested, the test had to be stopped before a drop of 70% in peak force was registered. In this case, the ultimate strain was computed considering to the stress and strain values at 30% and 50% drop in the peak force ($0.7\,f'_m$ and $0.5\,f'_m$ respectively) were used for this extrapolation. For 4 specimens, where the test terminated before a drop of $0.5\,f'_m$ was registered, fracture energy in compression was not computed.

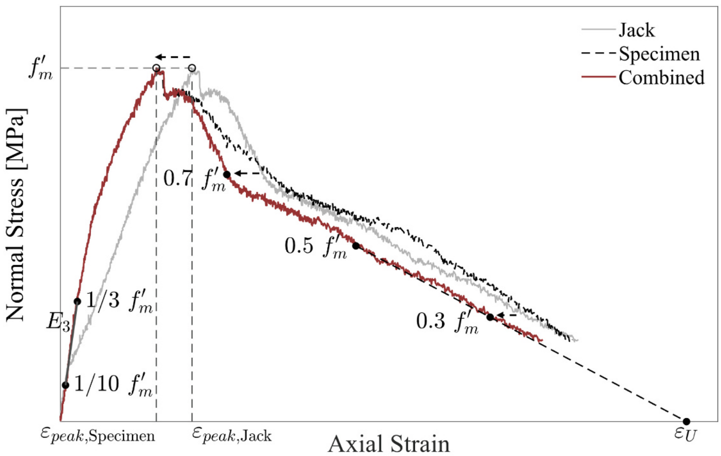

Fig. 3. Typical stress–strain response showing data from the LVDTs on the specimen (dashed line), jack displacement (solid grey line), and the combined stitched curve (red line). Key points used to evaluate elastic modulus (E_3) and fracture energy in compression are annotated.

3 Results and Discussions

3.1 Global Behaviour

Figure 4 shows the stress-strain response of a representative core along with the corresponding crack evolution at distinct loading stages. Typically, the initial portion of the curve exhibits linear-elastic behaviour. However, softening of the curve is initiated before the peak stress is reached, as cracks typically initiate in the head joints. In some cases, localised damage was observed near the capped ends at early stages of loading (Fig. 4c–d). If a head joint ended near or outside the cap-ends; then the cracking and separation of that region was even more pronounced. After the first cracking along the head joint, the cracking progressed to the cap. As the axial strain increased, this initial crack tends to widen and extend in the vertical direction. After the peak stress, some samples exhibit linear softening while some exhibit nonlinear softening. In the post-peak phase, the cracking pattern became more diffuse, with multiple cracks propagating across the specimen, ultimately leading to collapse. The cracking in the pre-peak phase did not seem to affect the compressive strength significantly as there was an almost immediate recovery in stresses.

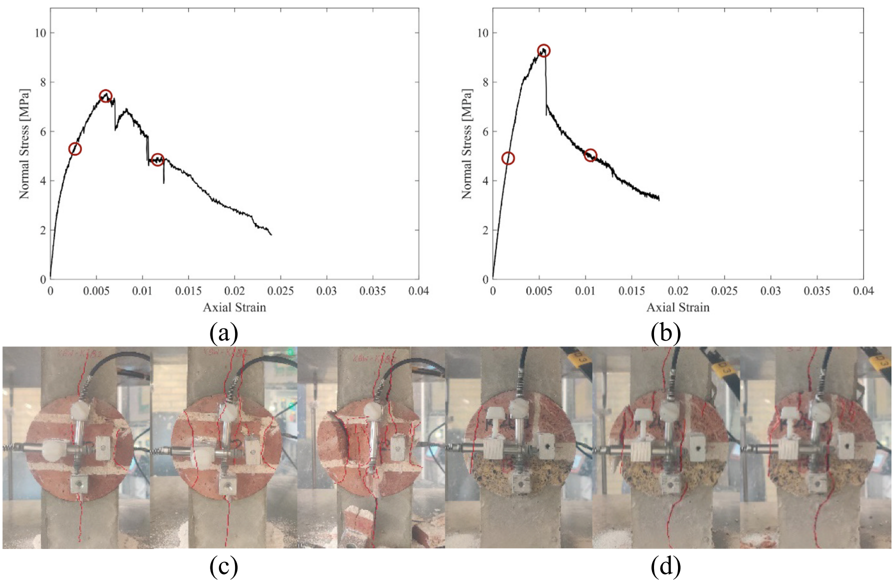

Fig. 4. Quay wall masonry cores under compression: (a) and (b) Stress-strain curve; (c) and (d) Typical crack pattern - onset of cracking, peak stress, towards the end of the test - specimens KBW_K2B2 (c) and B2_K2C1 (d).

Since the extraction of cores had not the primary intention of mechanical characterisation, a variety of bond patterns was observed leading to specimens with mortar head or bed joints terminating close to the cap-ends. This often resulted in initial cracking at or near the cap-ends (see Fig. 5), as the alignment of weaker mortar planes with the cap-ends introduced localised stress concentrations. While the central regularised zone remained engaged under load, these edge failures occurred prior to peak stress and were observed in specimens from both B2 and KBW. The premature cracking did not significantly affect compressive strength as it was typically followed by immediate force recovery. These observations highlight the importance of aligning the drill-head with the desired bond pattern geometry during extraction.

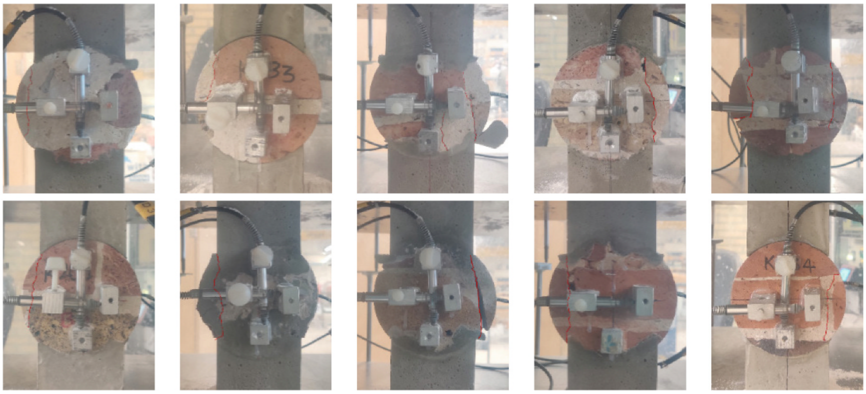

Fig. 5. Onset of cracking for cores with mortar head or bed joints aligned with caps ends.

3.2 Classification of Masonry Objects Based on Exposure Conditions

Previous study have shown that exposure conditions can influence the mechanical properties of masonry [4]. To consider this aspect, in this section the effect on compressive properties of exposure conditions along the height (above and below waterline) and across the thickness (external and internal side) of the wall are considered. Different classification strategies are considered and compared to find average properties for each masonry object associated to the exposure area. Such classifications are based on the assumption that each quay wall (B2 or KBW in this case) represent the same masonry typology, built with similar bricks, mortar, and bond pattern in a specific construction period.

Three classifications are considered (Fig. 6); Classifications A and B are used to evaluate variations along the height, while B and C are used to evaluate variations across the thickness of the wall. Classification A (Fig. 6a) is based on the metadata from the drilling agency [21], grouping samples extracted close to the waterline (<50 cm) with those extracted far above the waterline (>100 cm). Based on the mechanical properties obtained, classification B (Fig. 6b) groups samples extracted close to the waterline with those from below the waterline. Finally, classification C (Fig. 6c) defines four masonry objects - two along the height (as defined in Classification B) and two across the thickness (external and internal). It should be noted that the waterline in the canals of Amsterdam is regulated at 40 cm NAP (*Normaal Amsterdams Peil*), with surplus water pumped out via sluice gate outflows [24].

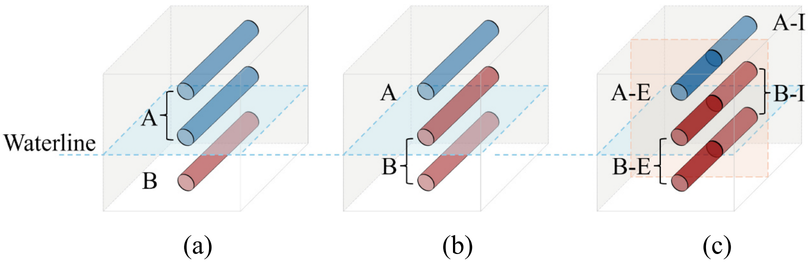

Fig. 6. Schematic representation of classification of masonry objects: (a) *Classification A* and (b) *Classification B* based on position relative to waterline (WL) – above water (A), and near/below water (B), and (c) *Classification C* based on through-thickness location - external (E) and internal (I) regions of the quay wall.

The Welch's *t*-test was used to assess which classification was statistically more representative and to evaluate differences between the groups in terms of mechanical properties as it accounts for unequal variances between groups. A threshold of $p < 0.05$ was used to determine statistical significance, indicating that there is less than a 5% probability that the observed difference occurred by chance.

Classifications A and B were compared to examine the effect of exposure conditions along the wall height. This was possible only for B2 quay wall, since for KBW masonry samples below waterline were not available. As shown in Fig. 7, classification B yielded a clearer separation in both strength and elastic modulus values compared to classification A, which displayed considerable internal variability. For compressive strength, both classifications were statistically significant ($p = 0.0075$ for A and $p = 0.0010$ for B), but classification B showed much lower intra-group variability. Regarding elastic modulus, classification B showed a significant difference between groups ($p = 0.0314$), while classification A did not ($p = 0.1078$). These results suggest that classification B provides a clearer and more statistically robust distinction between groups when compared to classification A.

Further, variation of properties across the wall's thickness was evaluated comparing classifications B and C. Due to insufficient number of samples across the thickness above the waterline, the through-thickness analysis considered only below waterline samples from both case studies. No significant difference in compressive strength (Fig. 8a) was observed between internal and external portions at both B2 and KBW locations ($p = 0.8930$ and $p = 0.3614$, respectively). Elastic modulus values were also comparable across both groups ($p > 0.5$).

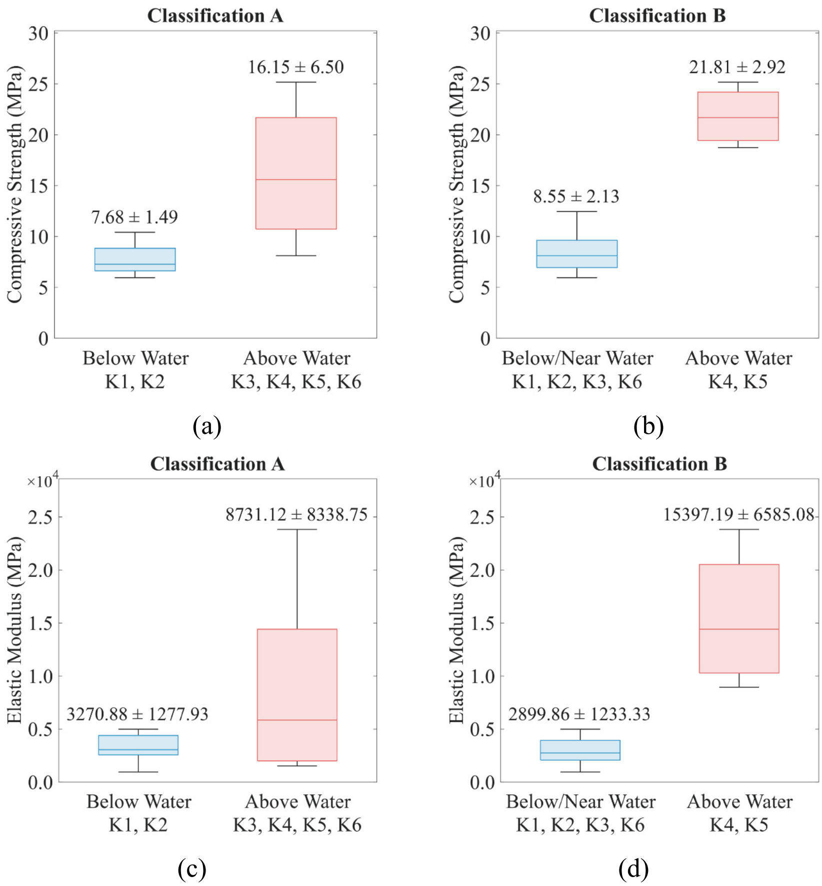

Fig. 7. Comparison in terms of compressive strength and elastic modulus distributions: (a) and (c) *Classification A* based on extraction location, and (b) and (d) *Classification B* informed by compressive strength clustering. Mean ± standard deviation values are annotated above the boxplot.

In conclusion, Classification B was found to be the most statistically significant classification of masonry objects. Samples extracted near the waterline exhibited compressive properties more similar to those from below the waterline. Unlike previous study on a bridge's pillar [4], no through-thickness effect was evident for the B2 location. These findings are to be considered preliminary due to the limited testing repetition per group (4 to 7) and the use of only 2 case studies. Therefore, Classification C (considering through-thickness variation) cannot be ruled out and will be retained for ongoing analysis.

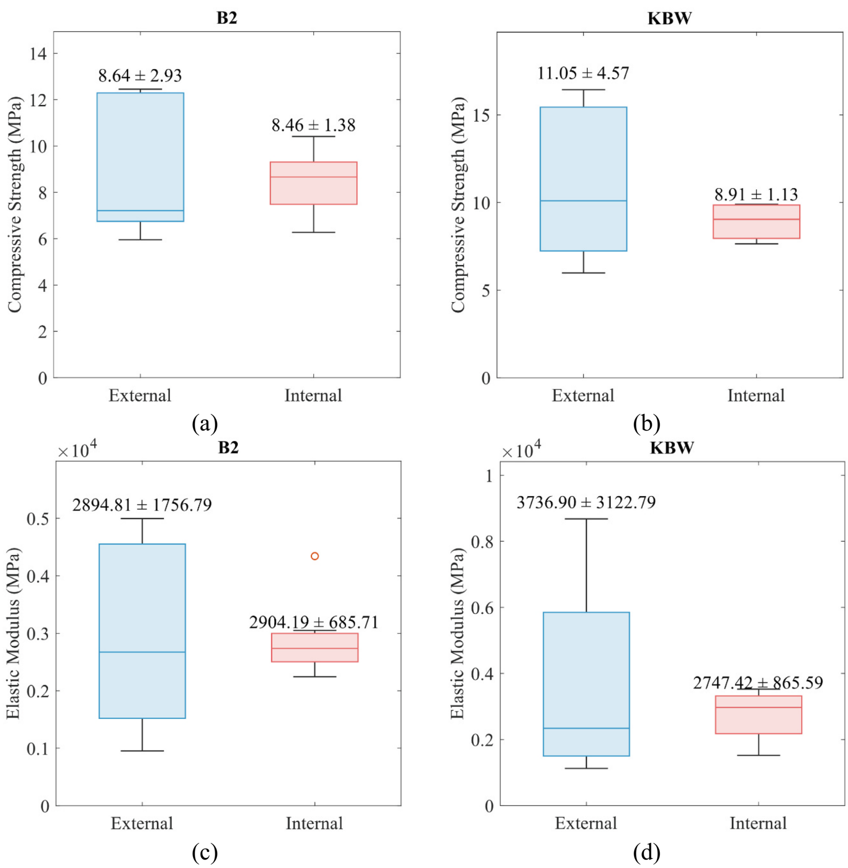

Fig. 8. Compressive strength values for internal and external samples below waterline considering classification C: (a) and (c) B2 and (b) and (d) KBW. Mean ± standard deviation values are annotated above the boxplot.

3.3 Effect of Exposure Conditions on Compressive Properties

Finally, the masonry cores were classified into masonry objects categorised by a) height relative to the waterline, and b) position through the wall thickness (see Fig. 6c). Figure 9 presents the mean compressive properties of the different masonry objects considering classification C. The highest compressive strength was recorded in samples from above the waterline at location B2, with an average of 21.58 MPa and a relatively low C.o.V. of 12.9%. In contrast, all other masonry objects located below or near the waterline show substantially lower average strengths, ranging between 8.4 and 10.9 MPa. Internal segments of masonry at both sites (B2-B-I and KBW-B-I) showed slightly lower strength values and relatively lower variability.

For the B2 quay wall, the compressive strength and elastic modulus values of the internal and external sections were comparable. Post-peak parameters, however differed: internal and external sections exhibited 47% and 54% lower mean values of fracture energy and strain at peak stress, respectively. These observations were characterised by a small number of tested samples and high variability in the results.

For the KBW location, the specimens extracted from the internal sections of the quay wall exhibited lower values of compressive properties than those from external section. Specifically, the internal section had 19%, 26%, 17% and 28% lower mean values of compressive strength, elastic modulus, fracture energy and strain at peak, respectively. However, the differences were moderate and largely fell within overlapping standard deviation ranges, suggesting limited statistical separation between the internal and external sections. Despite the overall trend indicating slight reductions in both strength and stiffness for the internal cores, the intra-group variability and small sample size call for cautious interpretation. Additional testing is required to validate these patterns.

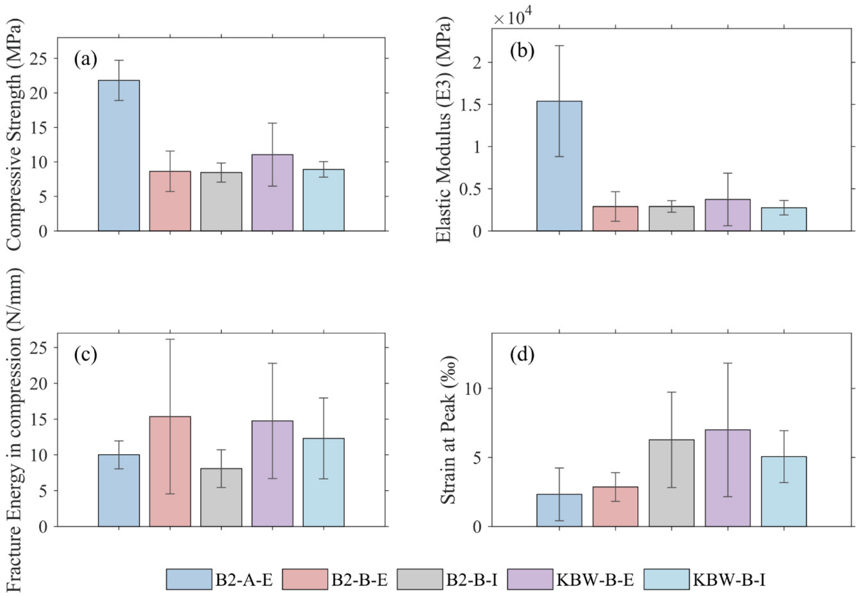

Fig. 9. Mean values of compressive properties for each masonry object: (a) Compressive strength, (b) Elastic modulus, (c) Fracture energy in compression, and (d) Strain at Peak.

4 Conclusions

The present work provides preliminary conclusions for the characterisation of multi-wythe masonry quay walls, based on selected case studies located in Amsterdam. Results of compressive tests on horizontally-loaded cores were analysed considering various classification of samples according to exposure conditions. The following conclusions are drawn:

- For the assessment of mechanical properties of quay walls, core testing is a promising technique, because it effectively aligns with the Municipality of Amsterdam's current practice of extracting cores to determine the geometry or thickness. This enables the reuse of these cores for mechanical characterisation. However, careful selection of the extraction locations can significantly improve the material characterisation efforts. In particular, attention should be paid in obtaining a sufficient number of samples for the various exposure conditions, and the bond pattern of cores should be selected carefully considering the testing configuration. Regarding the latter point, it is in fact found that the alignment of cap-ends with head or bed joints can cause localised cracking early in the loading stage. While this premature cracking outside the capped zone does not seem to affect the compressive strength, its influence on stiffness and post-peak behaviour remains unclear and should be further investigated through comparison with specimens with well-defined configurations (e.g., H-, T-, I- shape).

- Statistical analysis indicated a clear distinction in masonry properties relative to the waterline. Masonry near or below the waterline exhibited similar mechanical properties to each other, which were significantly lower than those of masonry extracted farther above the waterline. For the B2 case study, the above-waterline masonry showed substantially higher compressive strength and elastic modulus than the masonry from below or near the waterline, possibly due to lower environmental degradation. One hypothesis for this disparity is that the above-water portions might have undergone partial renovation at a later date (leading to improved strength and stiffness), although no archival records were found to substantiate such an intervention. However, given the limited sample size, additional testing and detailed microstructural analysis are needed to confirm and validate these differences.
- Comparisons across the wall thickness (external vs. internal sections) showed minimal differences in mechanical properties. Overall, no statistically significant difference was observed between internal and external masonry portions at the B2 site where strength and stiffness for core samples from internal and external sections were comparable. At the KBW site, the internal core samples did exhibit slightly lower compressive properties than the external samples; however, these reductions were modest and their values fell within overlapping standard deviation ranges, indicating that the through-thickness variations were not strongly pronounced. Considering the small sample sizes and high variability, these findings do not provide conclusive evidence of a systematic through-thickness effect, and further experimental investigation is warranted to draw definitive conclusions.

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