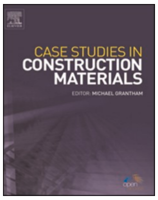
Case Studies in Construction Materials 17 (2022) e01504

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm



Methods for evaluating the technical performance of reclaimed bricks

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A R T I C L E I N F O

Keywords:
Deconstruction
Material properties
Reclaimed vintage bricks
Recovery
Reuse
Testing methods

A B S T R A C T

Reusing deconstructed materials and components can help to decrease the environmental burden of buildings. To safely reuse reclaimed items in new construction, methods are needed to reliably identify the essential technical properties of the deconstructed products. This paper looks at salvaged bricks and examines different indirect test methods to assess their properties. The explored test methods include visual observation, pitch of a sound, ultrasonic pulse velocity (UPV), and thin section. Reclaimed clay bricks and calcium silicate bricks were used in the research. They originated from four different buildings and from different kinds of structures. New bricks of the same kinds were also tested for reference and the properties were compared to the reclaimed ones. The assessed properties entail initial rate of water absorption, water absorption capacity, compressive strength, and freeze-thaw durability. The results show that it is possible to assess the deviation of properties and sort out exceptional bricks from a series with visual observation and pitch of a sound. The deviation of different properties can also be assessed with the help of UPV. A correlation was found between UPV and water absorption, compressive strength and freeze-thaw durability. Lower UPV values mean higher water absorption capacity and vice versa. Compressive strength of bricks is clearly lower when the UPV value is low and higher when the UPV is high. Bricks with lower UPV values (< 1.5 km/s) were also found to be freeze-thaw durable while those with higher UPV values (> 3.0 km/s) were found to be non-durable. Between the mentioned two values, the freeze-thaw durability varied. Thin section was only used to assess freeze-thaw durability and it was found to be unreliable as a method.

1. Introduction

Fired clay bricks are an ancient construction material, used to this day in many regions of the world. In terms of virgin material use, the industry's environmental impacts pertain mainly to the extraction of the natural clay raw material. With regard to CO_2 emissions, the impacts arise primarily from firing the moulded clay into bricks. One way to reduce the aforementioned environmental burdens of the industry is to substitute virgin production with circular economy-based approaches. The industry could introduce take-back schemes for bricks deconstructed from buildings scheduled for demolition, with the intent to reproductize them into construction

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https://doi.org/10.1016/j.cscm.2022.e01504
Received 9 June 2022; Received in revised form 16 September 2022; Accepted 22 September 2022

products.[1] According to [1], reusing one brick could save up to 0.5 kg of CO_2 emissions. Comparing the CO_2 value of a reused brick [2] to that of a typical value for virgin bricks [3] suggests that the emissions of a reused brick may account for as little as 1.5 % of the CO_2 of a new brick.

However, in order to build buildings out of salvaged bricks that are safe and sustainable in the long term, there is a need to identify the material properties of the bricks reliably, cost-efficiently and in a non-destructive way. Such testing must take into account that the properties of salvaged vintage bricks may vary more than those of virgin products made with modern manufacturing processes. Different indirect test methods can be a way to uncover the properties of reclaimed bricks on the deconstruction site and if needed, to select a sufficient number of specimens for potential further testing. Indirect test methods, such as ultrasonic pulse velocity (UPV) and microstructural analysis, are also commonly used in studying the properties of construction materials, such as concrete (e.g. [4–6]). Correlations between different indirect test methods and the properties of virgin and reclaimed bricks have also been previously shown by several researchers [7-12]. In these studies, the results have varied and different correlations between same methods and properties have been obtained.

Most of the existing literature is on new bricks. Typically, research has focused on mechanical properties (e.g. [7,11,12]), but durability properties have also been studied (e.g. [10,13]). Literature on reclaimed bricks is sparse, though some rare works exist. Park [14] investigated the bond between mortar and bricks, and the effect of bricks' different cleaning methods on the bond. In doing so, they also looked at the water absorption of bricks. Dizhur et al. [9] studied the mechanical properties of vintage bricks; while Cobîrzan et al. [8] examined the mineral composition thereof, which is connected to efflorescence. Thus, existing literature on vintage bricks is on singular properties.

The purpose of the current study is to determine whether a correlation exists between various indirect test methods and all relevant properties of salvaged bricks. The results from using four indirect test methods are compared to the properties determined with the help of four direct test methods. The aim is to find out how suitable and reliable different indirect and non-destructive test methods can be for assessing the properties of salvaged bricks intended for reuse. The studied properties include initial rate of water absorption (IRA), water absorption capacity, compressive strength and freeze-thaw durability. First, the water absorption properties have an effect on bricklaying and the bond between mortar and brick, which are related to the technical performance of the structure [15-17]. Second, the compressive strength indicates the strength of the brick, which is important for the durability and load-bearing capacity of the structure [18]. Third, the freeze-thaw durability is a one of the most significant deterioration mechanisms of masonries in Finland, where the current study is situated. These properties are assessed by a variety of indirect test methods, which were selected based on previous research. They include the pitch by ear, visual appearance (hue), ultrasonic pulse velocity (UPV), and thin section analysis, the last of which was only used to assess the freeze-thaw durability.

The paper's novel contribution is to investigate the applicability of indirect test methods for reclaimed bricks, covering the whole spectrum of relevant properties simultaneously. Unlike in previous studies, the goal is also to evaluate the necessary sample sizes for different indirect and direct test methods. Finally, in assessing the applicability of the different indirect test methods, the study takes into account the feasibility on (de)construction site conditions, which is crucial for their practical implementation.

2. Materials and methods

2.1. Brick specimens and their preparation

Various reclaimed and new bricks were used as specimens (Fig. 1). Reclaimed bricks were collected from four different buildings, and originate from their facades and partition walls. Solid and cored clay bricks were deconstructed from facades, whereas solid clay bricks and calcium silicate bricks were deconstructed from partition walls. The salvaged bricks were approximately 40–90 years old, depending on the donor building. In addition to the deconstructed bricks, new bricks were used for reference. The new bricks were selected to match the type and dimensions of the reclaimed bricks. A total of 20 bricks from each series were selected for the tests. The bricks were marked by the brick type and numbered individually from the visually lightest to the darkest. Table 1 gives the markings, numbers and the details of the bricks.

It has been shown e.g. by Park [14] that the cleaning method has an effect on IRA, i.e. a more effective cleaning leads to a higher rate. However in the current research, the effect of cleaning methods was not studied. All the reclaimed bricks were cleaned using the same method: a hammer and a chisel.

2.2. Dimensions and dry weight

The bricks were measured according to European standard [19] by using procedure b, in which the dimensions are taken from the midpoint of each side of the brick. The bricks were initially dried to constant mass in an oven for 96 h at 108 °C, after which the bricks were measured and weighed to determine the dimensions and the dry weight.

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[1] Only a few pioneering companies, such as the Danish Gamle Mursten and the Swedish Brukspecialisten (which partners for this purpose with Gamle Mursten), already do this on an industrial scale.

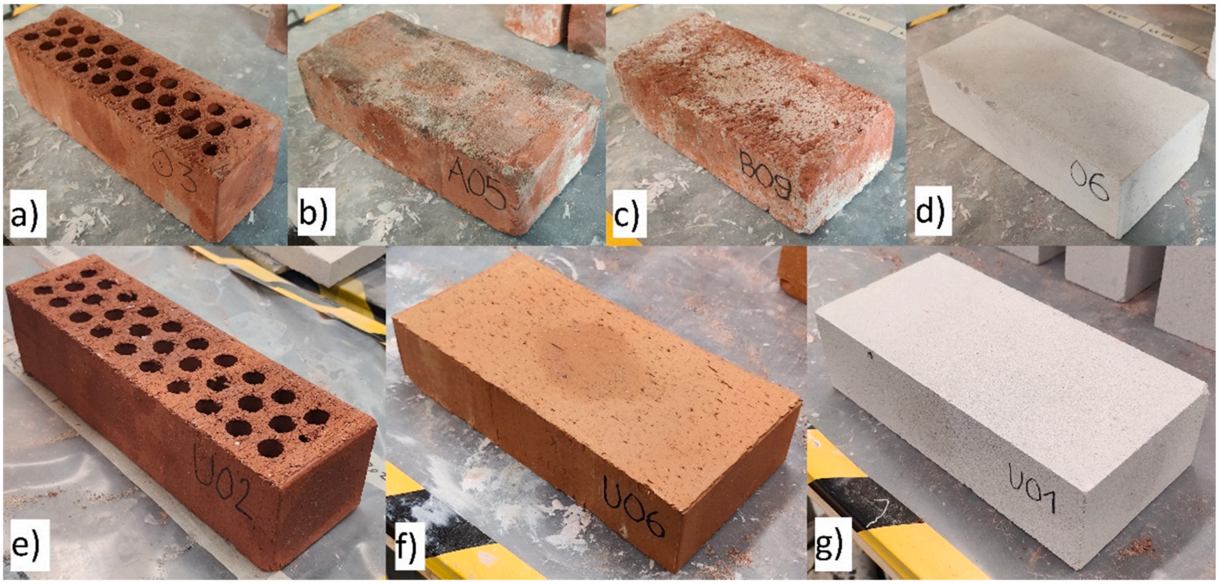


Fig. 1. Brick series a) MRT85(R), b) NT(A)(R), c) NT(B)(R), d) NKH(R), e) MRT75(U), f) PT(U) and g) NKH(U), see Table 1.

Table 1
Details of the bricks used in the research.

Brick type	Marking[a]	Reclaimed/new	Age (approx.)	Notes
Cored clay brick	MRT85(R) (from 1 to 20)	Deconstructed from a facade	40	Lighter bricks from 1 to 10 and darker bricks from 11 to 20
Solid clay brick	NT(A)(R) (from 1 to 20)	Deconstructed from a facade	90	Numbering from lightest to darkest
Solid clay brick	NT(B)(R) (from 1 to 20)	Deconstructed from a partition wall	70	Numbering from lightest to darkest
Solid calcium silicate brick	NKH(R) (from 1 to 20)	Deconstructed from a partition wall	40	–
Cored clay brick	MRT75(U) (from 1 to 20)	New	–	–
Solid clay brick	PT(U) (from 1 to 20)	New	–	–
Solid calcium silicate brick	NKH(U) (from 1 to 20)	New	–	–

[a] The markings originate from Finnish product names, and they describe the brick type. MRT stands for standard-sized cored brick, the number gives the height of the brick in mm. NT is an old abbreviation for standard-sized solid clay bricks, and PT is the new abbreviation for these types of bricks. NKH means standard-sized calcium silicate bricks. The U after the marking means it is a new brick and the R means it is a reclaimed brick.

2.3. *Initial rate of water absorption (IRA)*

After determining the dimensions and dry weight, the bricks were tested for the IRA according to SFS-EN 772–11:2011 [20]. The bricks were immersed in water for 60 s after which they were weighed to determine the increased mass. Because of the rough surface of salvaged solid clay bricks, all solid clay bricks were immersed in 10 mm of water, while all others were immersed in 5 mm, which is in accordance with the standard. The IRA was calculated by using the increased mass, immersion time, dry weight and gross area of the bed surface using Eq. (1).

$$c_{w,i} = \frac{m_{so,s} - m_{dry,s}}{A_s \bullet t_{so}} \times 10^3 \tag{1}$$

where A_s is the gross area of the bed surface, $m_{dry,s}$ refers to the dry weight of the specimen, $m_{so,s}$ refers to the increased mass after immersion, and t_{so} is the immersion time.

2.4. *Water absorption*

After being tested for the IRA, the bricks were tested for the water absorption. The test was performed according to SFS-EN 772–21:2011 [21]. Clay bricks were immersed in cold water for 24 h, and calcium silicate bricks were immersed for 48 h. The surfaces of the bricks were wiped with a damp cloth before weighing the increased mass. The water absorption was determined by using the dry weight and the weight after being immersed using Eq. (2).

$$W_s = \frac{M_s - M_d}{M_d} \times 100 \quad \% \tag{2}$$

where M_S is the weight after being immersed in water and M_d is the dry weight of the specimen.

2.5. *Ultrasonic pulse velocity (UPV)*

The UPV was measured through each side of the specimen and an average of the readings was used for determining the UPV value of each brick. The UPV testing was done on the air-dry bricks after being dried in an oven for 72 h at 108 °C. Before the UPV testing, the bricks were stored in a standard condition room at 23 °C and 50 % relative humidity. The UPV testing was performed by using Matest S.p.A. Pocket ultrasonic concrete tester, which measures the time of the ultrasonic pulse between two 55 kHz transducers (Fig. 2). Grease was used to improve the contact between transducers and the surface of the specimen.

The UPV was calculated by using Eq. (3).

$$V = S/t \tag{3}$$

where S is the distance travelled by the ultrasonic pulse and t is the time of the ultrasonic pulse.

2.6. *Pitch by ear*

Each series of bricks was sorted by ear based on the pitch of a hammer blow, with the exception of the PT series, the individual bricks of which all sounded identical. Solid bricks were struck in the middle of the bed surface and cored bricks in the middle of the side surface. The pitch was determined by ear. The brick with the highest pitch was given number 1, so the larger the number of order of a brick is, the lower its pitch is.

2.7. *Thin section analysis*

Thin section analyses were carried out from each series of salvaged clay bricks. A total of three bricks were selected for testing from the series based on the results of the UPV tests: the bricks with the highest, lowest and an average UPV result. The thin section analysis was performed to assess the freeze-thaw resistance of the specimen according to VTT Research Notes 1624 [22], which provides four different classes depending on the microstructure of the brick:

0 = no cracking
1 = wide and sparse cracking
2 = short, narrow and frequent cracking
3 = abundant and large cracking.

Eight-centimeter-long pieces were cut from the selected bricks and sent to an accredited external laboratory for the frost resistance analysis based on thin section. The remaining part was tested for freeze-thaw resistance following the procedures given in Section 2.9.

2.8. *Compressive strength*

The compressive strength testing of the bricks was performed according to SFS-EN 772–1:2011 +A1:2015 [23]. A Toni Technik

Fig. 2. Ultrasonic testing setup.

compressive strength testing machine was used in the research. 10 bricks from each series of bricks were selected for the test based on the UPV results, targeting bricks with different UPV results.

Before loading the bricks, their bed surfaces were ground to even and the bricks were dried to the air-dry condition. The air-dry condition was achieved by drying the specimens at 105 °C for 72 h, after which the bricks were cooled at room temperature (23 °C) for 24 h. Each specimen was laid in the middle of the plate of the test machine and loaded with a loading rate of 0,3 MPa/s, which was continued until visual damage occurred. Brick series NT(A) and PT exceeded the capacity of the testing machine (3000 kN), so these series were cut in two same-sized pieces. The pieces of the bricks were laid one on top of the other, and then loaded. The compressive strength was calculated by using the maximum load of the test and the surface area of the brick. Eq. (4) was used in the calculation

$$f_b = \frac{F}{A} \tag{4}$$

where F is the maximum compressive load of the test and A is the loaded surface area of the brick.

2.9. Freeze-thaw resistance

The bricks which were not selected for the (destructive) compressive strength test were instead tested for freeze-thaw durability, which, in case the bricks are not freeze-thaw durable, also destroys the specimens. The test was performed according to Finnish national standard [24] for clay bricks and according to European standard [25] for calcium silicate bricks.

The bricks were immersed in 15–20 °C water before the test. The clay bricks were immersed for 24 h to a depth of half of their height, after which the water surface was raised above the height of the bricks for 48 h. The calcium silicate bricks were immersed for an hour to a depth of a quarter of the height, after which the water surface was raised up to the halfway of the height. After one hour, the water surface was raised to three quarters of the height and the bricks were immersed fully in water after 24 h and removed after another 24 h.

After being immersed in water, the bricks were placed in the freeze-thaw chamber where the specimens were subjected to repeated cycles of freezing and thawing. The bricks were frozen to − 15 °C in 4 h and this temperature was maintained for 2 h. After the freezing, the bricks were thawed in 15–20 °C water for an hour. The freeze-thaw cycle was repeated 25 times and the visual damage was assessed. The bricks were classified from 0 to 3, where 0 stands for a freeze-thaw durable brick (no damage), 1 means there is small damage, 2 means large damage and 3 means that the brick is in two or more pieces.

2.10. Sample size

The sample size for UPV tests can be assessed by using Eq. (5).

$$n = \frac{4 * z^2 * \sigma^2}{W^2} \tag{5}$$

where z is a standard z-score for the chosen level of confidence, σ is a mean deviation and W is a chosen margin of error.

For freeze-thaw durability tests, the Eq. (6) was used, where the proportion is estimated and not the mean as in Eq. (5).

$$n = \frac{4 * z^2 * p(1-p)}{W^2} \tag{6}$$

where p is the percentage of durable bricks in the specimens.

3. Results and discussion

3.1. Dimensions and dry weight

The average dimensions and dry weight of each brick series (n = 20 for each series) are given in Table 2.

The table shows that the new bricks and the calcium silicate bricks have lower mean deviation than the reclaimed clay bricks. The

Table 2
Average dimensions and dry weight of the brick series.

Brick series	Length [mm]	Width [mm]	Height [mm]	Dry weight [g]
MRT85(R)	285,3 ± 2,0	84,9 ± 1,4	85,4 ± 0,9	2846,6 ± 24,2
NT(A)(R)	265,5 ± 3,9	125,4 ± 2,6	74,6 ± 1,0	4343,7 ± 93,9
NT(B)(R)	265,6 ± 5,2	127,2 ± 4,0	76,4 ± 1,3	4365,8 ± 149,8
NKH(R)	270,9 ± 0,2	129,6 ± 0,2	74,2 ± 0,4	4814,1 ± 55,9
MRT75(U)	285,8 ± 1,0	85,8 ± 0,4	75,0 ± 0,4	2639,1 ± 10,6
PT(U)	256,6 ± 0,3	122,3 ± 0,3	57,6 ± 0,3	3651,3 ± 13,3
NKH(u)	270,2 ± 0,3	130,6 ± 0,3	75,2 ± 0,4	4896,6 ± 67,4

difference between the new and old bricks indicates that older manufacturing processes have not been of as uniform quality as with new bricks. Also, the clay bricks deconstructed from partition walls (NT(B)(R)) have the highest mean deviations, which may be explained by the use of second-rate bricks in partition walls.

3.2. Initial rate of water absorption

The results of the direct IRA test are presented in Fig. 3.

The figure demonstrates that the salvaged clay bricks (NT[A](R) and NT[B](R)) showcase the highest deviations in IRA. The new MRT75(U) series exhibit the largest mean IRA value, while the deconstructed calcium silicate bricks possess the smallest mean IRA value. Next, the correlation is discussed between these results and those from the studied indirect methods.

3.2.1. Correlation with visual appearance

The series MRT85(R), NT(A)(R) and NT(B)(R) have visible differences between individual bricks, which enabled sorting the bricks within the series by their color. By observing the bricks with the highest, average and lowest IRA value from each series of bricks, it could be identified that darker bricks exhibit lower IRA values (Fig. 4).

Consequently, it is possible to assess the difference of IRA values between individual bricks of the same series by their visual appearance and to so select bricks with exceptional IRA values for further tests. The observed correlation between the color and the IRA can be explained with the manufacturing process, in which the firing rate influences a brick's porosity. At higher firing temperatures bricks get a darker color as well as a greater amount of larger pores, which decrease the water absorption properties including the IRA. In addition to the firing temperature, the clay used in the manufacturing process influences the IRA [26,27].

3.2.2. Correlation with pitch by ear

The order of bricks sorted by ear by the pitch of a hammer blow were compared to the IRA results. The results are presented in Fig. 5.

The pitch varies between the brick series as well as between individual bricks. In general, the lowest sounds are found on the new cored bricks MRT75(U), which exhibit the highest IRA. The highest sounds are exhibited by the PT(U) series, which showcase the lowest IRA for the clay bricks. The reclaimed clay brick series MRT85(R), NT(A)(R) and NT(B)(R) have the largest differences between the highest and the lowest pitches, which correlates with the high deviation of the IRA results. The calcium silicate bricks exhibit negligible differences between the highest and the lowest sounds as well as between the new and the salvaged series.

Thus, the deviation of the IRA values can be assessed by the pitch by ear. In addition, Fig. 5 shows that the highest sounds by ear have the lowest IRA values, and the lowest sounds have the highest IRA values. So, the pitch by ear can also be employed as a proxy to sort bricks by their IRA.

3.2.3. Correlation with UPV

A linear correlation between the IRA and the UPV results is presented in Fig. 6.

The figure reveals that the IRA cannot be assessed reliably by the UPV. With $R^2 = 0{,}39$, the results are not close to the regression line but scattered on a wide area. Nevertheless, the UPV can be employed to assess the deviation of the IRA results. A large deviation in the UPV results corresponds to a large deviation in the IRA results.

3.3. Water absorption

Fig. 7 gives the results of the direct water absorption test for each series of bricks.

Similar to the IRA, the reclaimed clay bricks have the highest deviation in water absorption. The cored brick series MRT75(U) and MRT85® have the lowest mean value of the water absorption, while the highest values are found in the series NT(A)(R), NT(B)(R), NKH(R) and NKH(U). Next, the correspondence between these results and those acquired with indirect methods is explored.

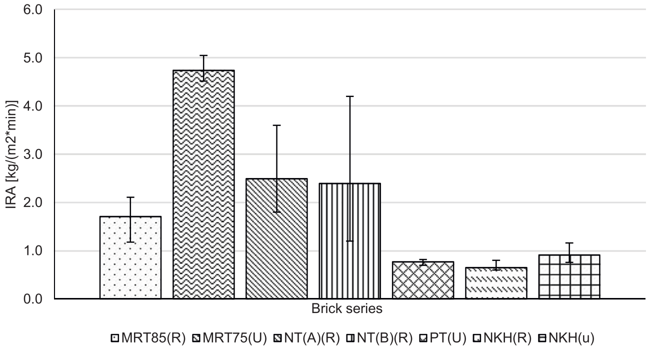


Fig. 3. IRA of each series of bricks.

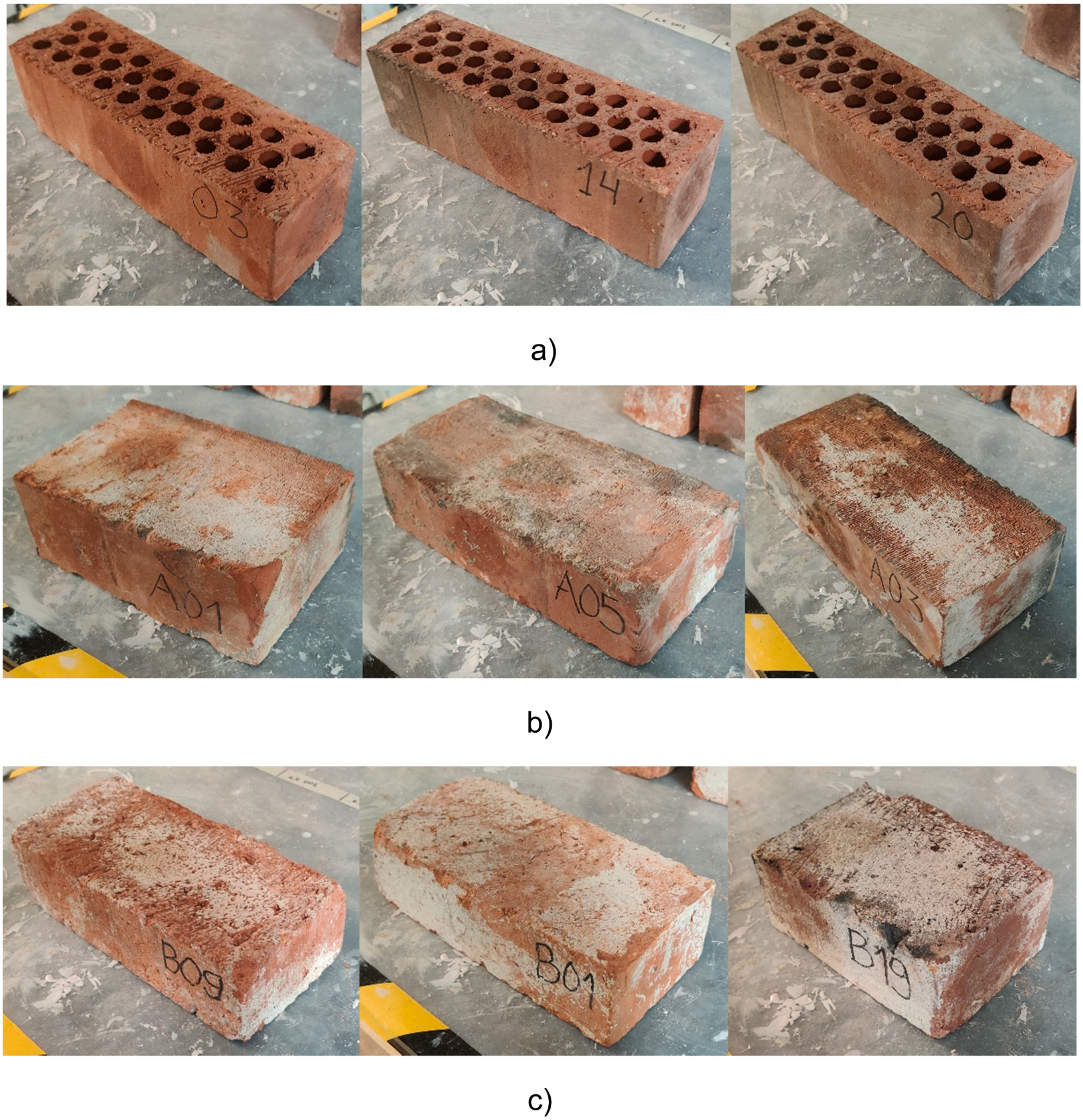


Fig. 4. The bricks with the highest, average and lowest IRA values in the series a) MRT85(R), b) NT(A)(R) and c) NT(B)(R).

3.3.1. *Correlation with visual appearance*

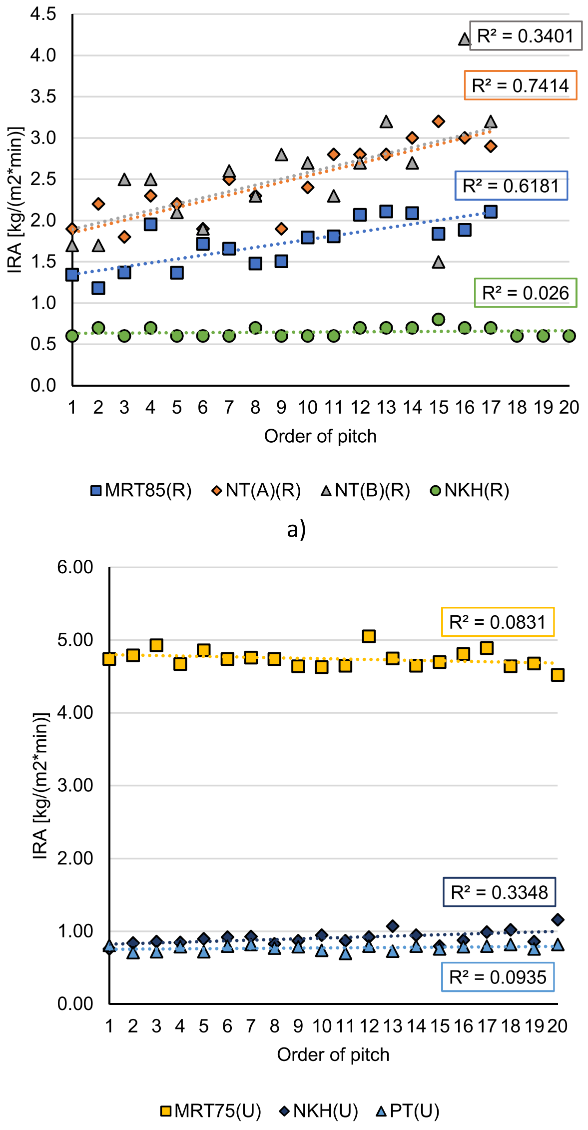
The hue of the deconstructed clay bricks, which could be sorted in order by their visual appearance, was examined for correlation with the water absorption by selecting the bricks with the highest, average and the lowest water absorption (Fig. 8).

The bricks with the highest water absorption has the darkest color, which is a result of the firing temperature used in the manufacture process. Its effect on the water absorption is similar to the IRA. The reasons for the observation are the same mentioned in Chapter 5.2.1 [26,27]. It can be concluded that by examining their hue, it is possible to assess the water absorption capacity of bricks and to select exceptional bricks from the series for possible further studies.

3.3.2. *Correlation with pitch by ear*

A correlation between the pitch by ear and water absorption was looked for and found by plotting the results on the same graph (Fig. 9).

As the Fig. 9 shows, the highest pitches correlate to the lowest water absorption capacity and vice versa. The brick series with the



a)

b)

Fig. 5. Correlation between IRA and pitch by ear, a) salvaged bricks and b) new bricks.

highest deviation in water absorption also have the largest difference between the highest and the lowest pitches; these are the salvaged solid clay bricks (NT[A](R), NT[B](R)). The deviation in water absorption can be assessed by the difference between the highest and the lowest pitch. Consequently, sorting the bricks by the pitch by ear enables selecting the most and least absorbent bricks from a series for further studies.

3.3.3. Correlation with UPV

The correlation between the bricks' water absorption capacity and UPV results are presented in Fig. 10.

The results from the individual series are set in parallel, which means that each series has a similar correlation between the results. The correlation is best demonstrated by the deconstructed solid clay bricks (NT[A](R), NT[B](R)), which have the highest deviation in the results. The results show that within a series, lower UPV values correspond to a higher water absorption capacity. If all series are investigated together, as one, the finding is different. Then, lower UPV values correspond to a lower water absorption capacity. The findings indicate that the series and different types of bricks have differences between one another and each series must be studied individually.

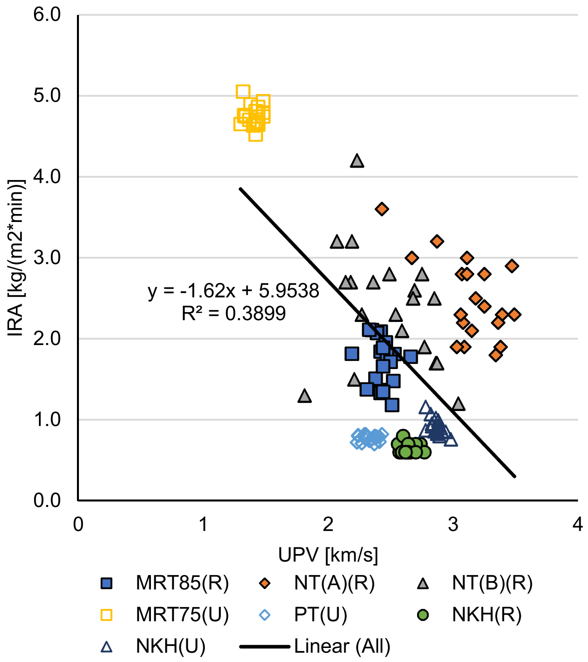


Fig. 6. Correlation between UPV and IRA.

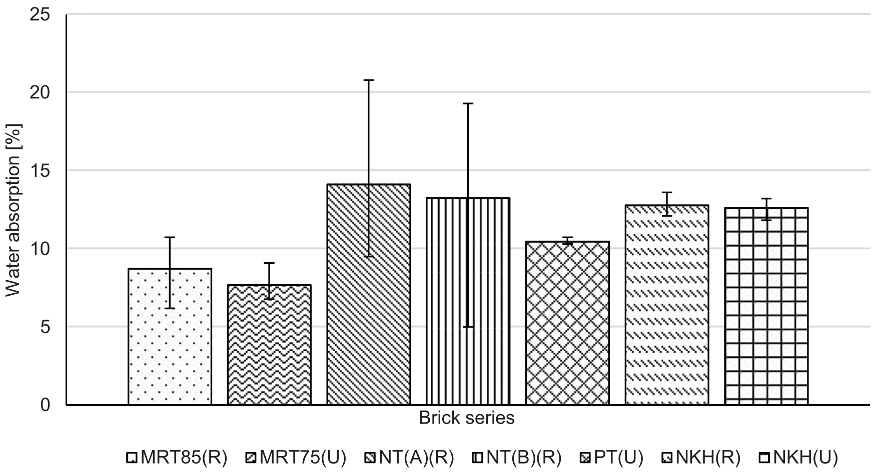


Fig. 7. Water absorption results for each series of bricks.

3.4. *Compressive strength*

Fig. 11 gives the results of the direct compressive strength tests.

Clearly the strongest brick series are the NT(A)(R) and PT(U) series, while the new cored clay bricks (MRT75[U]) are noticeably weaker than the others. The highest deviation in the compressive strength was identified in the reclaimed solid clay brick series NT(A)(R) and NT(B)(R), while the smallest deviation occurs in the MRT75(U) series. Other series' deviations fall between the two extremes and they are of a similar magnitude with one another. Next, it is discussed how these findings match with those of the indirect tests.

3.4.1. *Correlation with visual appearance*

The compressive strength test results were compared to the visual observations to identify if there is a connection between the two. Noticeable visual differences occur only on the reclaimed clay bricks.

The most noticeable color differences occur in the MRT85(R) and NT(B)(U) series (Fig. 12). The series NT(A)(R) also has color differences between individual bricks but the difference occurs only on the surfaces as a result of surface impurities, and the core is the same color. As previously mentioned, the color depends on the firing temperature and the clay used in the manufacturing. Higher firing

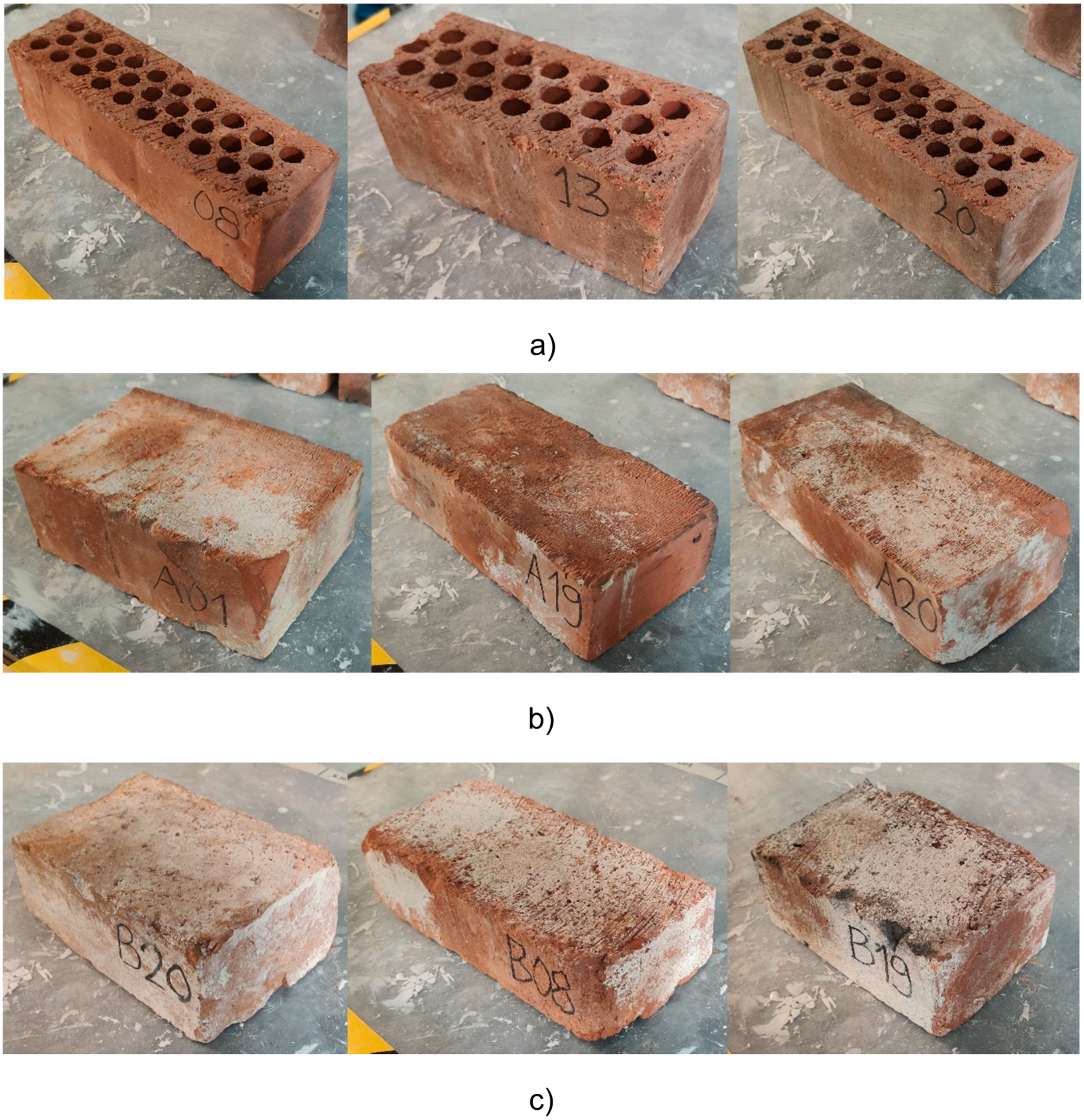


Fig. 8. The bricks with the highest, average and the lowest water absorption capacity from the series a) MRT85(R), b) NT(A)(R) and c) NT(B)(R).

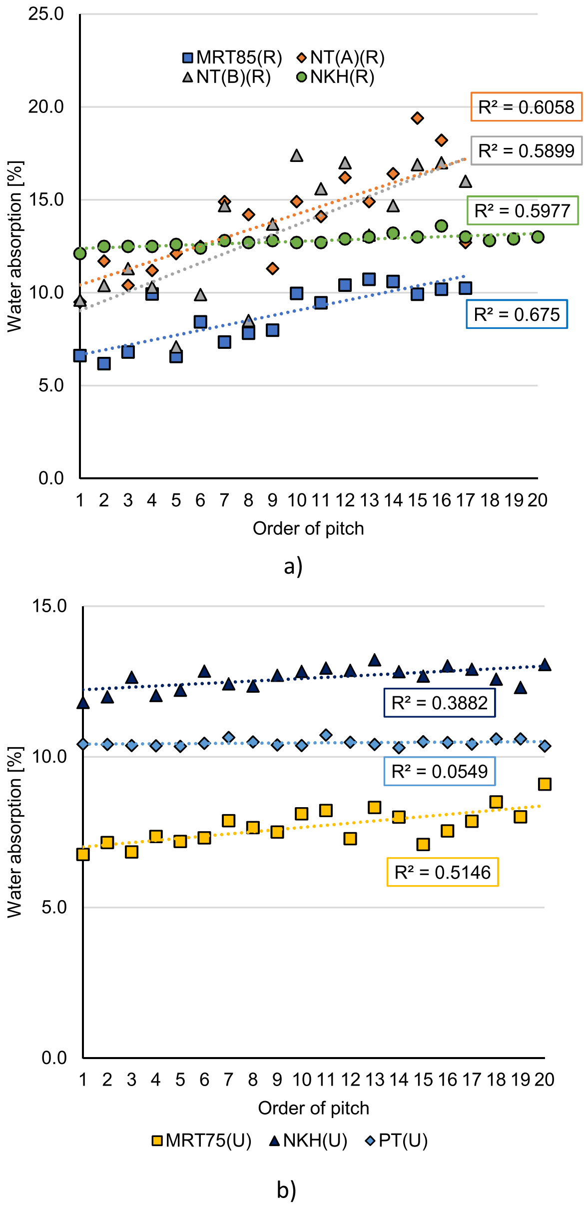
temperatures increase bricks' compressive strength [28].

The brick series are sorted by their hue from the lightest to the darkest. Fig. 12 demonstrates that the compressive strength increases with larger brick numbers, denoting that the darker bricks are stronger than the lighter bricks. Thus, the hue is a way to sort the bricks from the weakest to the strongest, which helps to limit potential further tests to the weakest bricks. Naturally, no exact values can be determined with the help of the visual appearance, so when values are needed, further study as direct test is required.

3.4.2. Correlation with pitch by ear

Fig. 13 shows the relation between the measured compressive strength and the pitch by ear.

As seen in the figure, the compressive strength increases when the pitch of a sound is higher, which means that the pitch can be used for approximating compressive strengths of individual bricks within a series. From the brick series can be selected the weakest or the strongest bricks by selecting the lowest or highest sounds. Also, the deviation of the compressive strength can be assessed by the difference between the highest and lowest sound. The higher the difference is the higher is the deviation.



a)

b)

Fig. 9. Correlation between water absorption and pitch by ear, a) deconstructed bricks and b) new bricks.

3.4.3. *Correlation with UPV*

An exponential correlation between the UPV and the compressive strength of the bricks can be seen in Fig. 14.

The results settle exponentially so that a higher UPV means a higher compressive strength. Thus, the UPV can be utilized to identify strong and weak bricks. With a UPV value over 3.0 km/s the bricks are substantially stronger (mostly over 60 MPa) than the other bricks in the research, and with a UPV value under 1.5 km/s the bricks are clearly weaker (mostly under 20 MPa). The results also demonstrate that within a brick series, the deviation of the UPV results correlate with that of the compressive strength. A higher deviation in the UPV also means a higher deviation in the compressive strength.

3.5. *Freeze-thaw resistance*

Table 3 lists the bricks after the direct freeze-thaw tests classified according to the occurred visual damage.

The freeze-thaw test results vary between the brick series. The cored clay bricks and calcium silicate bricks, whether new or reclaimed, were found durable, while the reclaimed solid clay bricks of the NT(A) series were in two or more pieces. Only the NT(B)(R) series exhibit both durable and nondurable bricks, which may be due to the previous structure where the bricks did not have any demands for freeze-thaw resistance; thus the variation in quality is extensive. Also, the new bricks in the PT series proved nondurable

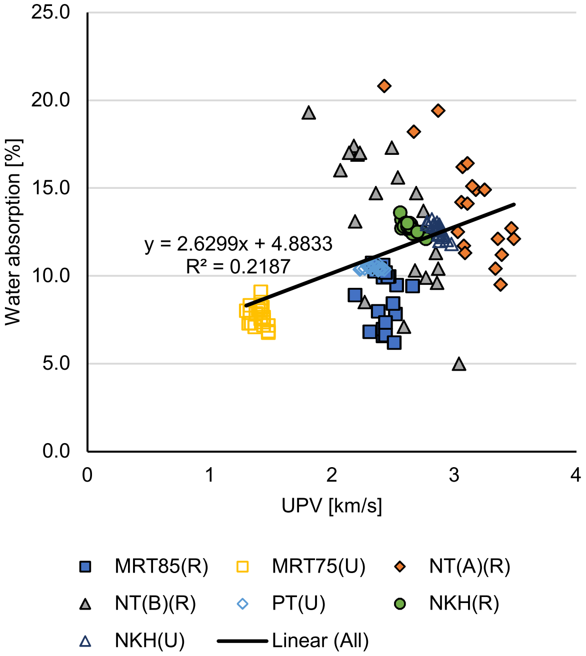


Fig. 10. Correlation between UPV and water absorption.

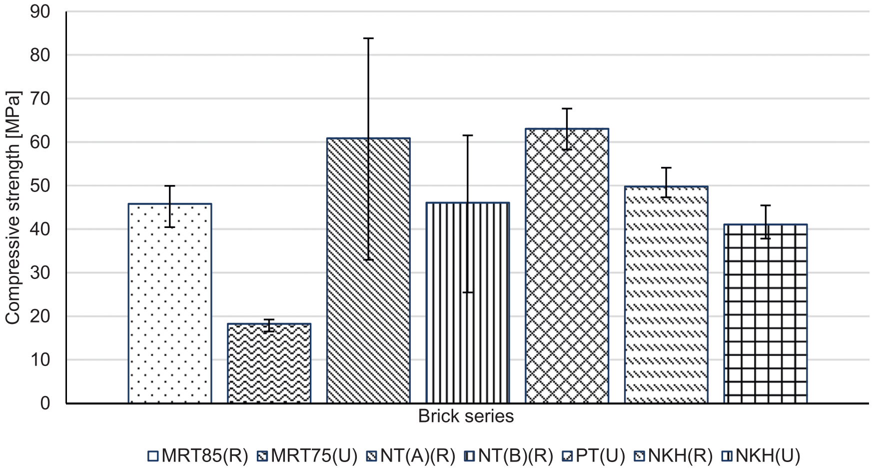


Fig. 11. Compressive strength of each series of bricks.

because they are not manufactured to be freeze-thaw durable.

The calcium silicate bricks were further tested for compressive strength to see if the performance of bricks exposed to freezing and thawing differed from that of non-exposed bricks, as required by the SFS-EN 772–18:2018 [25] standard in the absence of visual damage. Fig. 15 provides the results and reveals that the compressive strength is similar in both cases.

Next, the results of the direct freeze-thaw tests are compared to those of the indirect methods.

3.5.1. *Correlation with visual appearance*

The only series to have variation in both the hue and the freeze-thaw durability is the NT(B)(R). The light-colored bricks sustained the freeze-thaw test apart from one specimen. The darker bricks proved not to be freeze-thaw durable, indicating that the porosity is a more significant factor for freeze-thaw durability than the strength. Also the MRT85(R) series had lighter and darker bricks, however all of them sustained the freeze-thaw test. The NT(A)(R) series had hue differences on the surfaces but the cores of the bricks had the same hue, and all of them broke. There are no noticeable hue differences in the other brick series. Based on these results, the color alone cannot be deemed a reliable indicator for freeze-thaw resistance.

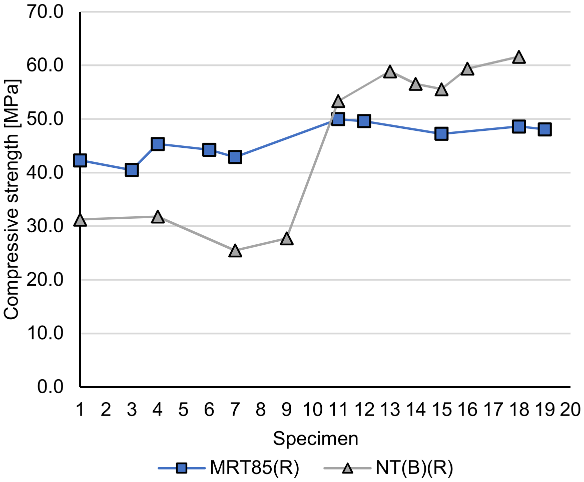


Fig. 12. Compressive strength of MRT85(R) and NT(B)(R) series.

3.5.2. Correlation with pitch by ear

The only two series to exhibit differences in individual bricks' freeze-thaw resistance are the solid brick series NT(B)(R) and PT(U). Out of these two, only the NT(B)(R) series also gave different pitches by ear. Fig. 16 juxtaposes the freeze-thaw durability class of the bricks in the series to their order of pitch.

As can be seen, the results are unregular. Thus, it is not possible to assess the freeze-thaw durability of an individual brick with the help of the pitch.

3.5.3. Correlation with UPV

Fig. 17 gives the freeze-thaw resistance class of the bricks as a function of their UPV value.

The UPV measurements exhibit a connection with the freeze-thaw resistance. Generally, freezing damaged the bricks with higher UPV values more than those with lower UPV values. Overall, the correlation is more regular within individual series than across all the series. From the results it can be deemed that the bricks with UPV values over 3 km/s were damaged in the test and bricks with UPV values under 1.5 km/s proved durable. Between these two UPV values, the freeze-thaw resistance varied.

3.5.4. Correlation with thin section analysis

The microstructural indexes based on thin section analysis were compared to the freeze-thaw durability classes acquired by direct testing. Table 4 juxtaposes them with one another; however it must be taken account that the indices and the classes are not directly comparable because the index is based on the microstructure and the class is based on the visual damage from the test in this research.

There is a remarkable difference in the microstructural indexes and the freeze-thaw durability classes. For one, the microstructural indexes suggest the MRT85(R) series is not durable, but the direct freeze-thaw test did not incur any visual damage on the specimens. In addition, the NT(A)(R) series exhibit various microstructural indexes even if the bricks were crumbled into two or more pieces after the freeze-thaw test.

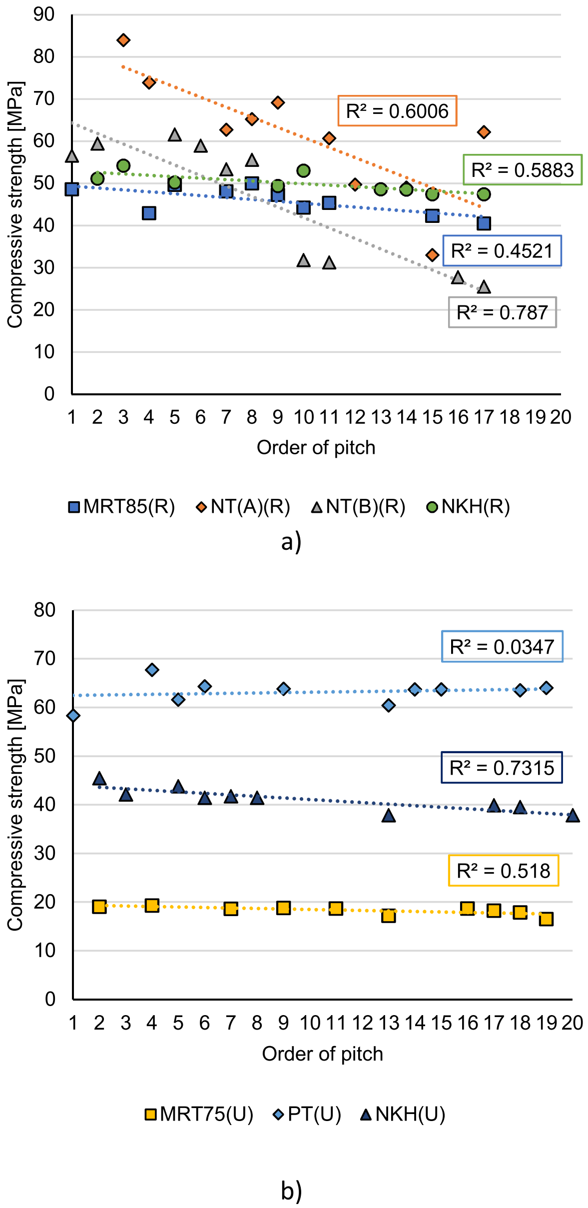
The only connections between the microstructural indexes and freeze-thaw durability classes were observed with NT(B)(R) series. Microstructure of the brick number 20 was widely cracked, which correlates with the damage after the freeze-thaw test. Also, the narrow cracking in the microstructure of the brick number 19 matches the smaller damage incurred in freeze-thaw test. The brick number 2 did not have any visual damage after the freeze-thaw test, which corresponds to its microstructure index.

Nevertheless, according to the results, there is generally no correlation between the microstructural index and the visual damage after the freeze-thaw durability test. Wide and large cracking in the microstructure does not necessarily denote weak freeze-thaw durability.

3.6. Applicability and sample size of indirect test methods

Each indirect test method used in the research gave different results depending on the studied property and the brick series. Applicability of the indirect test methods is assessed in Table 5. It is recommended to use several indirect test methods to get more reliable results with a smaller amount of work. Combining the assessment of visual appearance or the pitch by ear with UPV increases the reliability while reducing the amount of work, required sample size, and cost. The reliability increases if the first method can be used for distinguishing exceptional bricks out of the series before using the second method.

Using indirect test methods for studying properties of bricks is economical, but it is essential to choose the right sample size. Some uncertainty is always present in random sampling from a population, but uncertainty can be decreased by selecting as accurate and reliable test methods and random samples as possible and by using a sufficient number of samples. The sufficient sample size depends



a)

b)

Fig. 13. Correlation between compressive strength and order of pitch, a) salvaged bricks and b) new bricks.

on the property and the accuracy of the test method. For example, in terms of compressive strength, it is usually crucial to uncover the minimum compressive strength present in a batch of bricks. It can be obtained by sorting the batch by the bricks' visual appearance or by their pitch. After the bricks with the lowest compressive strength have been identified this way, the UPV can be used on them. This increases the reliability of the results in comparison to pure random sampling.

It is worth mentioning that the figures for pitch presented in this study cannot be directly used for assessing other bricks. This is because the figures do not consider specific values for pitch, only their order from the lowest to the highest, and all the bricks in a batch are needed to determine this order. The method itself is, however, replicable for any batch of bricks. Moreover, the possibility remains that certain types of bricks will typically exhibit specific pitch values. Determining this will require further studies and larger sample sizes.

The bricks to be studied should be sorted by the known properties and the structure. Bricks from various structures are usually from different batches, which means the properties are also different. To get the best information about the brick series, it is necessary to sort the bricks by the batch and known properties. For example, bricks from façades and partition walls or from different buildings should be kept separate. Moreover, the current study's results suggest that vintage bricks manufactured before 1980 can showcase noticeably more deviation than newer bricks. So, the necessary sample size also varies with the age of bricks.

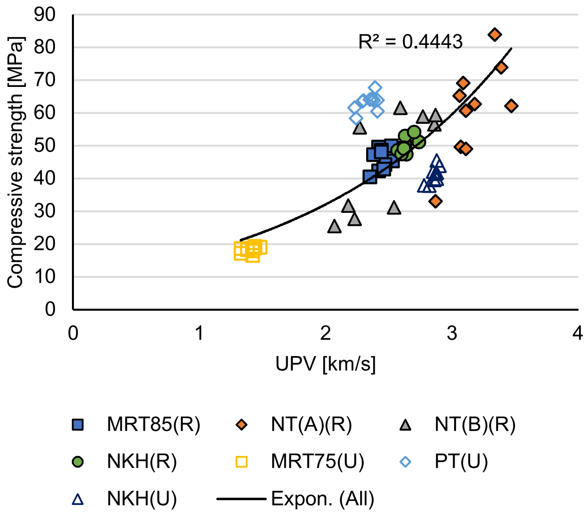


Fig. 14. A correlation between UPV and compressive strength.

Table 3
Individual freeze-thaw resistance class (0–3) of each tested brick, where 0 is a freeze-thaw resistant brick and 1–3 are non-resistant.

Brick series	Freeze-thaw resistance class									
MRT85	0	0	0	0	0	0	0	0	0	0
NT(A)	3	3	3	3	3	3	3	3	3	3
NT(B)	0	3	0	0	0	2	2	2	2	3
NKH	0	0	0	0	0	0	0	0	0	0
MRT75	0	0	0	0	0	0	0	0	0	0
PT	1	2	3	3	3	1	3	3	3	2
NKH(u)	0	0	0	0	0	0	0	0	0	0

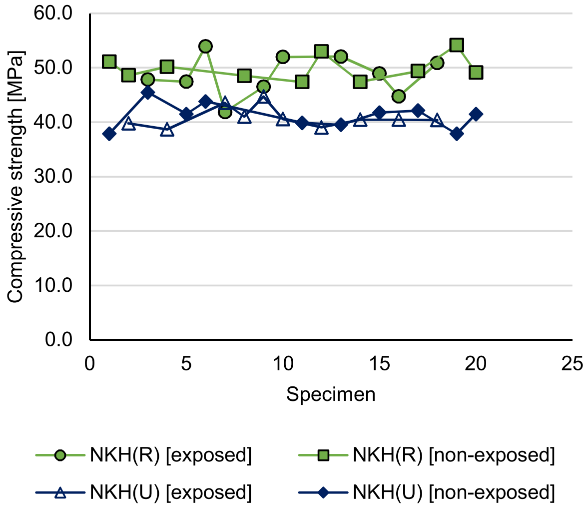


Fig. 15. Compressive strength of the freeze-thaw tested and non-tested calcium silicate bricks.

3.6.1. *Sample size for UPV*

For visual appearance and pitch by ear, all the bricks from the population should be studied because of the small amount of work required and passable/weak reliability. When using UPV, the age of bricks should be considered in the sample size. For older bricks, the sample size needs to be calculated on a case-by-case basis by using Eq. (5).

Because different UPV results were obtained for each series, the sample size needs to be calculated separately for each series by using their individual mean deviation. These are shown in Table 6, using a 95 % confidence level and a 10 % margin of error, which

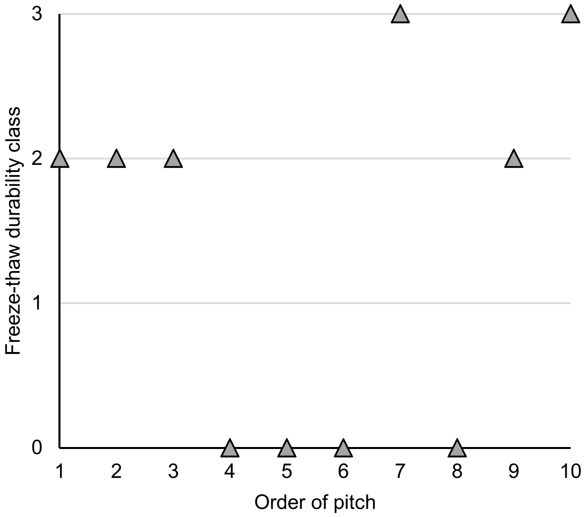


Fig. 16. Correlation of freeze-thaw durability class and order of pitch in the NT(B)(R) series.

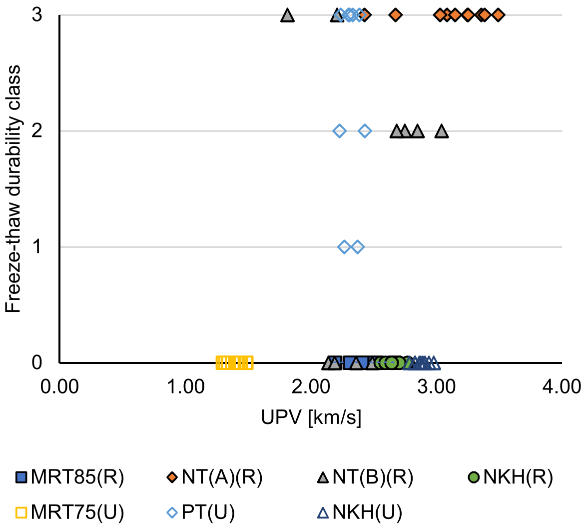


Fig. 17. Freeze-thaw durability class as a function of UPV.

Table 4
The microstructural index and the freeze-thaw durability class of the bricks selected for the thin section study.

Brick series (number)	Microstructural index	Freeze-thaw durability class
MRT85(R) (9)	3	0
MRT85(R) (13)	3	0
MRT85(R) (17)	3	0
NT(A)(R) (1)	1	3
NT(A)(R) (14)	0	3
NT(A)(R) (15)	2	3
NT(B)(R) (2)	1	0
NT(B)(R) (19)	0–1	2
NT(B)(R) (20)	3	3

means how many samples will not be within chosen confidence level. The 10 % margin of error was calculated from the mean UPV value for each series.

The required sample size for UPV testing depends on the brick series. From the results of Table 6, the largest sample sizes can be selected to act as suggested minimum required sample sizes for older and newer bricks (Table 7).

Table 5
Applicability and minimum sample size required of different indirect test methods.

Indirect test method	Property	Cost	Amount of work	Reliability	Minimum sample size required
Visual appearance	Initial rate of water absorption	Very low	Very small	Passable	All
	Water absorption capacity	Very low	Very small	Passable	All
	Compressive strength	Very low	Very small	Passable	All
	Freeze-thaw resistance	Very low	Very small	Weak	All
Pitch by ear	Initial rate of water absorption	Low	Small	Passable	All
	Water absorption capacity	Low	Small	Passable	All
	Compressive strength	Low	Small	Passable	All
	Freeze-thaw resistance	Low	Small	Weak	All
Ultrasonic pulse velocity	Initial rate of water absorption	Moderate	High	Passable	Table 7
	Water absorption capacity	Moderate	High	Passable	Table 7
	Compressive strength	Moderate	High	Good	Table 7
	Freeze-thaw resistance	Moderate	High	Good	Table 7
Thin section	Freeze-thaw resistance	High	Very high	Weak	144 (seeTable 8)

Table 6
Calculated sample size for each series.

Brick series	Mean UPV value	Mean deviation, σ	z (95%)	W (10%)	Minimum required sample size, n
MRT85(R)	2.43	0.10	1.96	0.24	3
NT(A)(R)	3.14	0.26	1.96	0.31	11
NT(B)(R)	2.48	0.33	1.96	0.25	28
NKH(R)	2.64	0.05	1.96	0.26	1
MRT75(U)	1.40	0.06	1.96	0.14	3
PT(U)	2.33	0.06	1.96	0.23	2
NKH(U)	2.87	0.05	1.96	0.29	1

Table 7
Minimum required sample size for UPV test depending on the age and type of brick.

Building year of the deconstructed building	Minimum required sample size for UPV test
> 1980 (or calcium silicate bricks)	3
≤ 1980	28

3.6.2. *Sample size for thin section analysis*

Table 8 determines the minimum sample sizes for thin section analysis, using the data of Table 4 as its input, with a confidence level of 95 % and a 0.5 margin of error.

The sample size for thin section analysis can be selected from the Table 8. The highest value (144) can be used for reclaimed clay bricks as a minimum required sample size.

3.6.3. *Sample size for direct tests*

Sample sizes can also be determined for direct tests. In Table 9, the sample size for each property test is calculated from the results of this study, with a confidence level of 95 % and a 10 % margin of error for the mean value by using Eq. (6). The p was calculated from the results of the NT(B) series because it had both durable and non-durable bricks. The calculated p was 60 %. A confidence level of 95 % and a 0.5 margin of error were used.

As the table shows, the minimum required sample size varies depending on the brick type and age. The older bricks need more than 100 samples for testing with a 10 % margin of error, except for freeze-thaw durability tests. A large minimum sample size means that using indirect test methods is more economical and time-saving than using direct test methods. Of course, when choosing the test method, it must be considered that the direct test methods are more precise and reliable than the indirect methods. The sample size for freeze-thaw durability tests was only obtained for the NT(B) series, and it can be used as a sample size for older bricks.

Table 10 suggests minimum required sample sizes for direct test methods. For vintage clay bricks manufactured before 1980, maximum values from Table 9 are adopted. For clay bricks produced after 1980 and for calcium silicate bricks, the minimum sample

Table 8
Calculated sample size for thin section analysis.

Brick series	Mean index value	Mean deviation, σ	z (95%)	W	Minimum required sample size, n
MRT85	3.00	0	1.96	0.5	0
NT(A)	1.00	1.00	1.96	0.5	62
NT(B)	1.33	1.53	1.96	0.5	144

Table 9
Minimum required sample sizes for direct property tests.

Brick series	Initial rate of water absorption	Water absorption	Compressive strength	Freeze-thaw durability
MRT85	45	49	8	0
NT(A)	61	70	85	0
NT(B)	141	140	162	15
NKH	14	1	4	0
MRT75	2	10	4	0
PT	5	1	3	0
NKH(u)	17	2	6	0

Table 10
Minimum required sample sizes for direct test methods depending on the age and brick type.

Property	Clay bricks from > 1980 (SFS-EN 771–1:2012 + A1:2015)	Clay bricks from ≤ 1980	Calcium silicate bricks (SFS-EN 771–2:2012 + A1:2015)
Initial rate of water absorption	10	141	–
Water absorption	10	140	6
Compressive strength	10	162	6 or 10 if coefficient of variation is $\geq$ 15%
Freeze-thaw durability	10[24]	15	12

Note: For calcium silicate bricks, the sample size for initial rate of water absorption is not determined in standards.

size can be drawn directly from standards because of small deviation in properties.

4. Conclusions

This research studied the applicability of different indirect test methods for assessing the properties of reclaimed vintage and new bricks, the exact value of which were obtained with direct test methods. Different conclusions were obtained for different properties.

About the properties it can be said that the deviation of the IRA of reclaimed bricks can be assessed by observing their visual appearance (hue), pitch by ear and with UPV. Exact values are impossible to obtain with the indirect test methods used in the research. The water absorption capacity of brick batches can be assessed by the UPV values. Lower UPV values correspond to higher water absorption than higher UPV values. The deviation of water absorption capacity can be assessed based on the bricks' visual appearance, pitch by ear and UPV. The compressive strength of bricks can be assessed with the UPV. Bricks with UPV values under 1.5 km/s are clearly weaker (mostly under 20 MPa), while those with UPV values over 3.0 km/s are noticeable stronger (mostly over 60 MPa). The weakest and the strongest bricks can be sorted out of a series by their visual appearance and pitch. All the indirect test methods used in the research are suitable for assessing deviation within brick batches. The freeze-thaw durability showed a correlation only with the UPV. Bricks with UPV values 1.5 km/s or under proved durable, and those with values over 3.0 km/s proved non-durable. The other indirect test methods studied in this research cannot be recommended for this purpose.

About the indirect test methods and sample sizes the conclusions were that brick batches must be sorted based on their origins and the batches studied individually because the properties can vary substantially between batches. Also required sample sizes for UPV and direct tests depend on the age and type of brick. Sample sizes given in standards can be used for newer reclaimed clay bricks (1980 onwards) and for calcium silicate bricks. For older vintage bricks, the sample size depends on the deviation of properties. Suggestions for the minimum sample size are provided in this study. Using various indirect test methods, applicability can be increased because reliability and economy improve by using more than one indirect test method.

Funding

The study was conducted in the Circular Construction in Regenerative Cities (CIRCuIT) project. The project has received funding from the European Union Horizon 2020 research and innovation programme under grant agreement No 821201.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

We thank Wienerberger Ltd (Juha Karilainen), Umacon Ltd (Vilma Wathén) and Consti Ltd (Olli Kalliokoski) who donated the bricks for this research. We are also grateful to our colleague Kari Pylkkänen from the brick laboratory of Tampere University who gave guidance on the implementation of the tests. The thin section analyses and the related assessment of frost resistance were performed by Koestus Ltd, the services of which were funded by the City of Vantaa under the CIRCuIT project, for which we are also grateful.

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