Developing advanced techniques to reclaim existing end of service life (EoSL) bricks – an assessment of reuse technical viability

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Abstract: Structural bricks are highly durable building products. However, brickwork is mostly demolished long before the end of its technical service life; the majority are crushed to form aggregate or else landfilled. Urban mining and circular economy are stimulating interest in the potential to recover structural products from end-of-service-life buildings for direct reuse. For brickwork, separating bricks from cement-based mortar, as opposed to lime-based mortar, without damage to bricks is a major barrier. This paper presents two advanced techniques based on saw cutting and punching, to demonstrate the technical feasibility of brick reclamation. Compared to new bricks, reclaimed bricks have similar visual appearance and their compressive strength differs by -4.8% to +40%. Design formula for compressive strength of masonry in current codes can be applied to reclaimed bricks. The reclamation process achieves reclaim rate of over 95% and has significantly lower energy consumption, and carbon requirements (<1%) relative to new bricks.

Keywords: Brickwork; Masonry; Reclaim; Circular Economy; Reuse; End-of-Service-Life

1 Introduction

The value of the global brick and masonry block industry is estimated at around $1,837 billion and growing. Clay bricks account for around 70% of total production (Transparency Market Research 2017). In the UK approximately 1.9 billion bricks are manufactured each year from a total demand of 2.5 billion (The Construction Index, 2018). Bricks are highly durable products and can maintain their structural properties for hundreds of years. However, many buildings and structures containing bricks are demolished long before the end of their technical service life with less than 5% of the 2.5 billion bricks demolished each year in the UK reclaimed for reuse. The majority are crushed and much of this is used to form aggregate or else landfilled (Kay and Essex, 2009). Whilst reducing the need for virgin aggregate, this practice loses much of the embodied energy and carbon and the potential to reclaim and reuse the bricks for further structural purposes. A major barrier to reclaim and reuse of brick is the accepted belief that it is technically impossible to separate the brick from cement-based mortar without damage to the brick. This contrasts to the well-established practice of separating bricks from with lime-based mortar which is a much weaker binding (BDA, 2014; Bouvier et al., 2013; Cristini et al., 2014; Gorgolewski, 2008; Pesce et al., 2013; Quagliarini et al., 2014; Serlorenzi et al., 2016; Sisti et al., 2016).

The volumes of structural products in building stocks however have led to a growing interest in whether such products could be reclaimed and re-used at some point in the future (Ucer et al., 2018). This concept of 'urban mining' forms a part of the wider concept of circular economy. The rationale of a circular economy is to increase the value derived from products, components and materials used within economic systems. This increased value in a circular economy derives from maintaining the integrity of a product at a higher level (technical and economic durability), using products longer (repeat use), cascading use in adjacent value chains and creating pure, high quality feedstock (avoiding contamination and toxicity). By doing so, this will also avoid losing embodied carbon and related environmental costs associated with its life cycle and avoid the need for new product within its attendant impacts.

It has been suggested that construction and buildings have the highest potential for circular economy innovation, value retention and creation opportunities (EMF, 2015). It is argued that in a circular building and construction economy, all end-of-service-life (EoSL) buildings are potential material banks and deconstructable to retain high value materials and products and, given their bulk/value ratio, repair and remanufacture of products from

EoSL buildings would be carried out and stored locally and then blended into new buildings also locally to minimise cost. To achieve this, however, new approaches will be required to product reclaim and remanufacture and demonstration of the technical feasibility and superior economic, material and social value from such a re-design against a base linear case or recycling.

This paper presents research findings on the technical feasibility using novel techniques to reclaim and reuse clay bricks bonded with cement-based mortar as the first stage in a circular economy building and construction system. The main body of this paper is structured in four sections. Section 2 outlines the technical challenges & barriers of reclaiming and re-using clay bricks with cement-based mortar and the specific objectives for the paper. Section 3 describes the novel saw cutting, punching techniques and shows the laboratory results from using these new techniques and the potential challenges in scaling up. Section 4 presents an assessment of mechanical properties of reclaimed bricks. Section 5 concerns the prospective availability of the new techniques.

2 Key technical challenges & barriers of reclaiming and re-using clay bricks with cement-based mortar

2.1 Demand

Brick reclaim and reuse has been largely driven by specific high value products (stone, heritage) and by aesthetic reasons to provide a particular character and a distinctive distressed appearance, being fully matured and weathered or natural patina (BDA, 2014), or forced by planning authorities to match the materials used in a historical building when maintenance, refurbishment or an extension is required. While there is a market for the resale of heritage bricks within the salvage sector, widespread reclaiming and reuse of clay bricks is a niche process within the demolition sector (Smith and Sawyer, 2013; Adams et al., 2017).

2.2 Design for deconstruction

Brick buildings constructed using cement-based mortar were not designed for deconstruction (Adams et al., 2017) and attempts to do so are considered to be time-consuming, labour-intensive and risk damaging the bricks. Conventional demolition practice is largely time and cost driven which, coupled with the relatively low unit cost of bricks, has made it unattractive to consider alternative or novel approaches to reclaim, reuse and remanufacture. Therefore, when such constructions reach their end of life, the bricks are crushed and recycled (Nordby et al., 2009; Cheng, 2016).

2.3 Cement-based mortar

A key technical challenge therefore relates to the type of mortar used (Addis, 2012). In clay brick masonry construction, bricks are normally bonded with two types of mortar, hydraulic lime-based mortar in historical masonry buildings (most commonly pre-1920) and cement-based mortar in modern masonry buildings starting from 1920s when ordinary Portland cement (OPC) became widely used in construction (Mortar Industry Association, 2013).

With lime-based mortar, the brick units bond weakly to each other thereby making their separation and reclamation relatively easier, which is further aided by the fact that lime-based mortar will degrade over time. Thormark (2000) reported that about 85% of the bricks with lime-based mortar can be perfectly separated. A rate of up to 2000 reclaimed bricks per person per day can be achieved by hand and, hence, it is commercially viable (Addis, 2012).

Even so, the existing separation and cleaning methods of old bricks bonded with lime-based mortar is mostly manually/half-automatically using a heavy/brick hammer and broad cold chisel or bolster (BDA, 2014), demolition hammer, or brick cleaning process via chemical reaction by using hydrochloric acid to remove stubborn mortar carefully without acid penetration into the brick (BDA, 2014). Although these methods are technically feasible, they are either labour-intensive or heavily rely on a skilled labourer to perform the work which limits the rate at which bricks can be cleaned. Furthermore, it would not be practical to reclaim on a brick-by-brick basis for massive constructions (Yeap et al., 2012). Individual case examples, however, illustrate the potential in reclaiming bricks. A total of 230 tonnes of bricks reclaimed from the deconstruction of two large Victorian houses, Putney, UK saved 200 tonnes embodied carbon. The reclaimed bricks were re-used in the construction of Jubilee Wharf, Penryn around 430 km away (BioRegional Development Group, 2017). The construction of the new BRE Building 16 - The 'energy-efficient office of the future', Garston, UK used around 80,000 reclaimed bricks to clad the new building, with the reclaimed bricks being supplied from a reclamation dealer less than 100 km away, creating sufficient environmental benefits to justify any additional time or costs (Addis, 2012).

The OPC-based mortar, especially of a high grade, is highly tenacious and retains relatively high bond strength with the brick surface hence is difficult to remove by existing mechanical or chemical reclaiming methods which are also likely to cause damage to the units (Hobbs and Hurley, 2001; Addis, 2012). Although brick-by-brick cleansing machines via mechanical vibration have been developed (Klang et al., 2003; Gregogy, 2005; KHR Company Ltd, 2017), they are more suitable for cement-based mortar of low grade and the process could still be time-consuming. In fact, various researchers (e.g., Addis, 2012; Iacovidou and Purnell, 2016) concluded that it was not feasible to reclaim bricks from modern cement-based mortar and separation was not practical in terms of its cost-effectiveness or environmental impacts. So far no effective way has been found to reclaim bricks with cement-based mortar from brick masonry blocks after demolition.

2.4 Quality assurance

Where bricks can be separated from cement-based mortar a further challenge is the testing and certification of properties to assure their quality before re-using. Unfortunately, no standardised guidelines or codes of practice currently exist to state the examination method by which to conduct performance evaluation and testing of reclaimed bricks.

This means that reusable load-bearing components are often forced to be applied to non-structural purposes unless they are thoroughly tested in certified laboratories. By using a proven technology for deconstruction i.e. reclamation of bricks, the quality assurance can be largely improved by applying standardized deconstruction practices, along with proper staff training (Hradil et al., 2014).

These challenges help to explain why there has been so little research or innovation to reclaim and reuse bricks from cement-based mortars, especially from masonry blocks. Despite this, there is no fundamental technical reason why bricks cannot be efficiently and cost effectively separated, hence this paper reports on the use and application of potential techniques of reclaiming bricks bonded by cement-based mortar. This forms part of the first stage of a three-year (2018-2021) research project **REgenerative BUILDings and products for a circular economy** (REBUILD), funded by the UK Engineering and Physical Sciences Research Council (EPSRC) to design new circular economy building systems. For this stage of the project and this paper, a review of potential techniques to reclaim structural clay bricks with cement-based mortar led to a focus on two possible approaches. The first was to adapt and extend saw-cutting techniques and the second was an entirely new method based on punching. This paper presents laboratory results of this research on two main aspects: (a) to investigate the technical feasibility, economic values and environmental impacts of these two techniques; and (b) to evaluate the performance of reclaimed bricks by comparison against original bricks to provide assurance of the quality of reclaimed bricks.

3 Technical feasibility of the new techniques

3.1 Saw cutting method

3.1.1 Trial of the cutting method

Saw cutting is an effective method of separating solid materials and is used widely in construction and demolition. A key challenge however is applying the technique to brick structures at a scale that would not damage the bricks. The development of this technique followed two steps. Firstly, trial tests on reclaiming bricks from small-scale masonry samples were conducted, noting environmental and economic impacts such as energy consumption of the process; secondly, the performance of reclaimed bricks was evaluated.

Two common types of diamond saw, i.e., a bench saw and a hand-held saw, were tried in the trial test. The bench saw, providing a bench for holding the cut objects, is more suitable for small-scale to medium-sized objects. The saw motor has a revolution of 3000 per minute. The portable hand-held diamond saw is more suitable for large immovable objects. However, the hand-held diamond saw was found to be unsuitable after a trial because it was difficult (i) to fix the brick specimen securely; and (ii) to provide water to suppress dust.

Figure 1 shows the bench saw set up. A base (1) was fabricated using steel plate and aluminium sections to hold the specimen. To allow for lateral adjustment of cutting depth and to ensure safety, two horizontal slots (2) were drilled on the vertical legs of the aluminium angle (3) and steel angle situated on the edge of the bench (4). The specimen/brick (5) is held tight through the lever (6) positioned on the top of the U-shaped aluminium section (7).

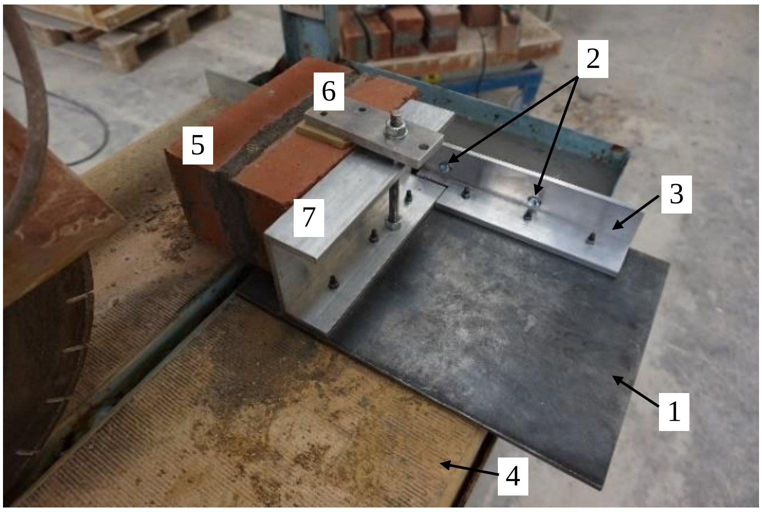


Figure 1 Bench saw with self-manufactured base for holding bricks

There were two technical challenges: removing all mortar in a single cut, and securing the brick to ensure parallel cutting.

Although a 2-mm-thick blade was able to easily cut through the 10-mm-thickness mortar joint, a thin layer of mortar sometimes inevitably adhered to the beds of the separated bricks. To clean the adhering mortar, the brick was held onto the base (Figure 1) and the position of the brick was adjusted via the two aforementioned slots so that the blade ran as closely to the brick-mortar interface as possible during cleaning. Due to unevenness of the brick surface, several attempts were usually necessary to recondition a brick to an acceptable reusable state. For the 178 reclaimed bricks, the average additional runs to clean the face, bed and head faces were 1.49, 0.44 and 0.76 per brick, respectively. The reason why an average value less than unity was obtained was that some faces of bricks were not bonded with mortar (Figure 2); thus requiring no additional runs for cleaning. Future improvements include using a specially-designed blade with greater dimensions/thickness to separate and clean the bricks simultaneously.

Furthermore, although the base provided a smooth surface to hold the bricks, the uneven faces (due to imperfection or adhering mortar) of the bricks made it difficult for the cutting plane to be parallel with the brick faces. A result is trapezium-shaped cross-sections of the reclaimed bricks after cleaning. Since aiming the blade precisely at the mortar-brick interface would be difficult and inefficient for reclaiming the bricks with uneven surfaces, a possible solution is to sacrifice a thin layer (less than 2 mm) of the brick. This is expected to have a minor effect on reusability because any minor dimensional changes of reclaimed bricks can be easily accommodated by the amount (thickness) of mortar.

3.1.2 Specimen preparation

After the trial tests to demonstrate the feasibility of the technique and to fine tune the setup, bonded brick specimens were prepared for reclaiming using saw cutting. The specimens consisted of three types as shown in Figure 2. Type 1 was the reference base and it consisted of two bricks and one bed joint. Type 2 had one bed and one head joint. Type 3 had multiple joints. For all three types, two types of bricks, i.e., perforated engineering bricks and frogged bricks were used.

The nominal dimensions of the bricks were 215×102×65 mm. The cement-based mortar types were designed to be M4 (general usage mortar designation (iii), for low-rise housing according to BS 8103-2:2013) and M12 (strong mortar designation (i), for free standing walls, in accordance with BS EN 1996-1-1:2005+A1:2012).

The cement-to-sand ratios of the two mortar types were 1:3 and 1:6 respectively. Fine sieved sand and high strength cement of 52.5N in strength class (BS EN 197-1:2011) were used to make the mortar.

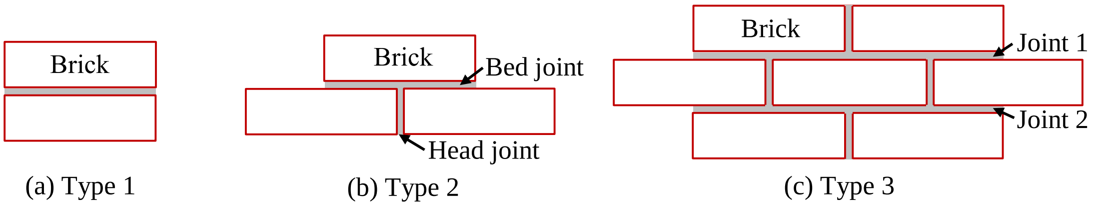


Figure 2 Schematic diagram of specimens for saw-cutting method

Table 1 summarises the specimens. For designation of the specimens, the first letter indicates the type of bricks ('F' for frogged bricks and 'P' for perforated bricks), the number following refers to the number of core holes, grade of mortar (M4 or M12) and the number after '-' indicates the specimen type according to Figure 2.

Table 1 Summary of specimen design (trial test of saw cutting)

Label	Brick type	Mortar class	Specimen type	Number	Bricks
FM12-1	Frogged	M12	1	14	28
P3M12-1	Perforated	M12	1	11	22
P3M4-1	Perforated	M4	1	6	12
P3M12-2	Perforated	M12	2	6	18
P3M4-2	Perforated	M4	2	6	18
P3M12-3	Perforated	M12	3	6	42
P3M4-3	Perforated	M4	3	6	42

3.2 Punching method

3.2.1 Trial of the punching method

The punching method of brick reclaiming was inspired by the hole punching approach in manufacturing goods using thin steel sheets. The strength of steel is about 30 times higher than that of cement-based mortar, so punching through mortar of 102.5 mm (width of brick) requires far less punching force compared to steel of a few millimetres thick. As with saw cutting, the key challenge is to apply this new technique to salvage old bricks effectively and free from damage. The development of the punching method went through three main stages. Firstly, designing, manufacturing, assembling of punching device were conducted. Secondly, lab trial tests on brick reclamation by using the small-scale masonry specimens, noting environmental and economic impacts of the reclamation process, followed by the performance evaluation of the punching process.

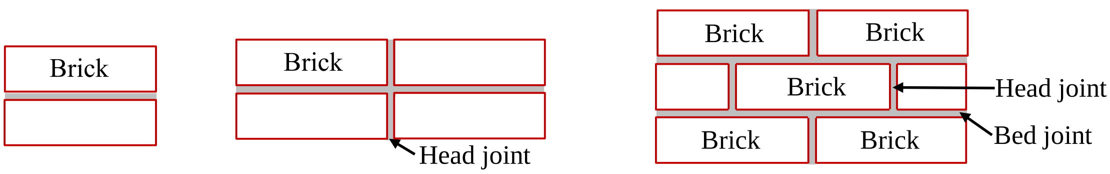
At this stage, no such a punching machine is available. Therefore, an Instron loading machine was used. A specially manufactured punching blade was inserted into the Instron which then applied a punching force to remove the entire thickness of mortar. After a series of trial tests, the blade size was finalised to be 50 mm wide and 8mm thick. For punching a normal mortar thickness of 10 mm, the 8-mm-thick blade was chosen to ensure that there was a minimum amount of tolerance so that the blade would not damage the brick. The 50 mm width allows flexibility and adjustment of punching along the width (102.5 mm) and length (215 mm) of a brick unit. With this blade width, two and four punches would be required in the brick width and length direction, with any major residual mortar either removed as part of the main punch or easily removed by an additional punch.

An important consideration in the punching system is to secure the brick assembly to eliminate its lateral movement. Punching is a dynamic process and may make the brick assembly move side way if not restrained. This would cause the punching blade to punch the brick instead of the mortar, thus making the punching process more difficult (due to brick strength greater than mortar strength) and damaging the brick. In our laboratory tests, a clamping device was used.

For perforated bricks, the infilled mortar in the core holes was easily removed by one strike of a hammer. In the future, a customised punching blade in line with the shape of the core holes could be developed as an additional reclaiming tool.

3.2.2 Specimen preparation

As with saw cutting, the punching method was applied to three different brick assemblies (shown in Figure 3), which represented one bed joint for simple trial test (see Figure 3 (a)), and large masonry pieces with stack bond and stretcher bond (see Figure 3 (b) and (c)). In each case cement-based M4 and M12 mortar types were used as with the saw cutting tests.



(a) Type 1 (b) Type 2 (c) Type 3

Figure 3 Schematic diagram of specimens for punching method

Fired clay bricks of different types ranging from facing bricks (Compressive strength varies from 21 to 60 MPa), Class A/B engineering bricks (Minimum compressive strength is 125/75 MPa for Class A/B) and common bricks (Compressive strength is around 40-50 MPa) were used. Both solid bricks and perforated bricks with three and five core holes were used. The dimensions of the perforated bricks were the same as used in saw cutting (215 mm long × 102.5 mm wide × 65 mm tall). Solid Pre-War Common bricks were also used. This type of bricks was used throughout the 19th and 20th centuries and is still used today usually for retro housing or repair of historical buildings. The Pre-War Common bricks (219 mm × 104.8 mm × 73 mm) are the former imperial standard brick adopted in 1965 (Jenkins, 2014).

Table 2 summarises the specimens for punching. For designation of the specimens, the first letter indicates the type of bricks ('S' for solid bricks and 'P' for perforated bricks), the number following refers to number of the core holes (for solid bricks, the number is neglected), the grade of mortar (M4 or M12) and the number after '-' indicates the specimen type according to Figure 3.

Table 2 Summary of specimen design (trial test of punching).

Label	Brick type	Mortar class	Specimen type	Number	Bricks
SM12-1	Solid	M12	1	6	12
SM4-1	Solid	M4	1	6	12
SM12-2	Solid	M12	2	3	12
SM12-3	Solid	M12	3	3	15
P3M12-1	Perforated	M12	1	6	12
P3M12-2	Perforated	M12	2	3	12
P3M4-2	Perforated	M4	2	3	12
P3M12-3	Perforated	M12	3	3	15
P3M4-3	Perforated	M4	3	3	15
P5M12-1	Perforated	M12	1	6	12
P5M12-3	Perforated	M12	3	3	15
P5M4-3	Perforated	M4	3	3	15

4 Performance evaluation of reclaimed bricks

BDA (2014) concluded that 'the use of reclaimed bricks should not be discouraged provided that users are conscious of their qualities and the associated property testing of re-used bricks is required….' The two main forms of evaluation are quality of appearance known as 'condition evaluation', to detect macroscopic flaws and cracks on the surface of the reclaimed bricks, and 'structural performance evaluation' concerned with strength and durability.

As shown in Figure 4 and Figure 5, the reclaimed bricks by both saw cutting and punching do not show any macroscopic flaw or crack and had the same quality of appearance as new bricks. Therefore, the focus of performance evaluation was on structural (mechanical) properties. For this purpose, compressive tests were carried out on both individual brick units and brick wallettes (miniature walls). Tests on individual reclaimed perforated bricks from both techniques included samples with the core holes cleaned and with residual mortar in the core holes.

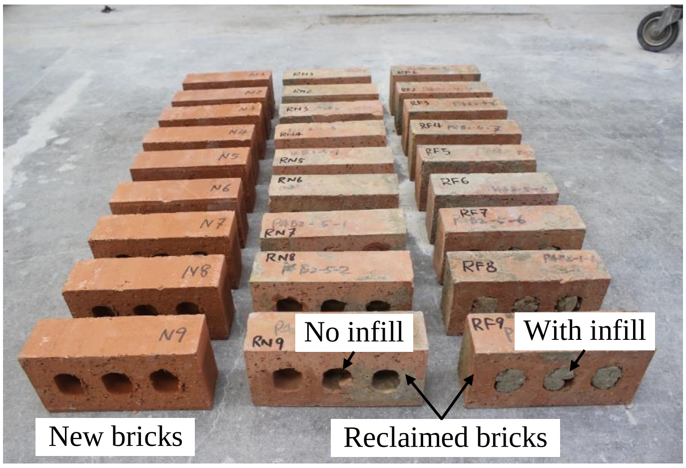


Figure 4 Appearance of new bricks versus reclaimed bricks by saw cutting method

(a) New brick

(b) Reclaimed bricks by punching without mortar infilled

(c) Reclaimed bricks by punching with mortar infilled

Figure 5 Appearance of new bricks versus reclaimed bricks by punching method

For wallettes using reclaimed bricks, the bricks were reclaimed from assemblies with M4 and M12 mortar (Figure 2 and Table 1) for saw cutting method, and from assemblies in Figure 3 and Table 2 for punching method. The new mortar for wallette testing was nominally of the same types (M4 and M12) as the original mortar before reclaiming. Note that for saw cutting method, the height of the wallettes was 365mm (made of 5 courses) due to the limitation of the loading machine; for punching method the height of the wallettes was 430 mm (6 courses of bricks) according to BS EN 1052-1:1999. Note that all the wallette specimens were capped for several days before testing, according to BS EN 1052-1:1999.

Table 3 summarises the wallette specimens for reclaimed bricks using saw cutting technique. For identification, ‘N’ and ‘R’ refer to new and reclaimed bricks respectively. Letters ‘P’ and ‘F’ denote perforated and frogged bricks respectively.

Table 3 Summary of wallette specimens for reclaimed bricks using saw cutting method

No.	Specimen label	Wallette description	Mortar class	Specimen number
1-1	NP3M12	Perforated new (3 core holes)	M12	3
1-2	RP3M12	Perforated reclaimed (3 core holes)	M12	3
2-1	NP3M4	Perforated new (3 core holes)	M4	3
2-2	RP3M4	Perforated reclaimed (3 core holes)	M4	3
3-1	NFM12	Frogged new	M12	2
3-2	RFM12	Frogged reclaimed	M12	2
4-1	NFM4	Frogged new	M4	1

Similarly, Table 4 summarises the wallette specimens for reclaimed bricks using the punching technique. For identification, 'N' and 'R' refer to new and reclaimed bricks respectively. Letters 'P' and 'S' denote perforated and solid bricks respectively.

Table 4 Summary of wallette specimens for reclaimed bricks using punching method

No.	Specimen label	Wallette description	Mortar class	Specimen number
1-1	NP5M12	Perforated new (5 core holes)	M12	3
1-2	RP5M12	Perforated reclaimed (5 core holes without mortar infilled)	M12	3
2-1	NP5M4	Perforated new (5 core holes)	M4	2
2-2	RP5M4M12	Perforated reclaimed (5 core holes with old M4 mortar infilled, bed joints with new M12 mortar)	M4 +M12	3
3-1	NSM12	Solid new	M12	3
3-2	RSM12	Solid reclaimed	M12	3

4.1 Mechanical test facilities

Figure 6 shows the compressive test setups for individual bricks and wallettes reclaimed using saw cutting. For the testing of individual bricks, one steel plate was grinded on both the top and bottom surface (within an error of 0.001mm) and placed below the tested brick, to provide a flat loading surface as required and to reduce the gap between the top and bottom platens. The loading rate was determined according to the specification in BS EN 772-1:2011+A1:2015.

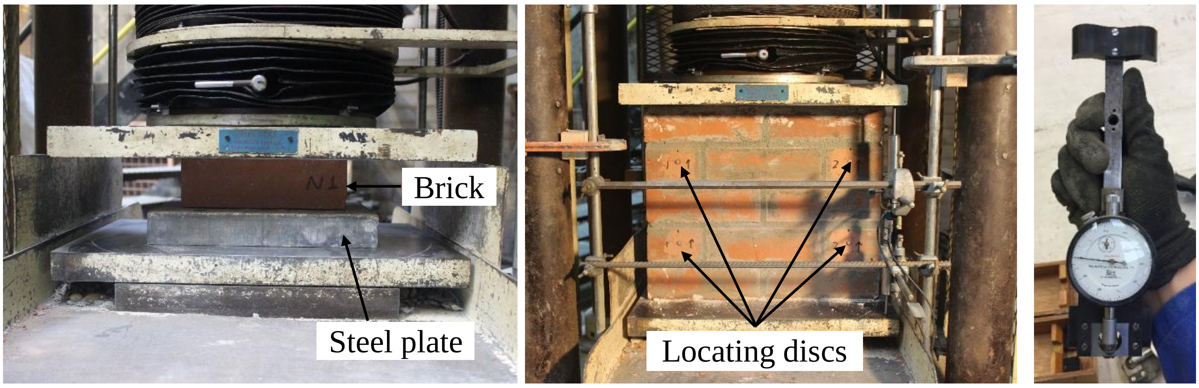


Figure 6 Mechanical test set-ups. (a) Testing of a brick, (b) Testing of a wallette, (c) DEMEC

During compressive testing of wallettes, the strain of the wallette was determined by using Demountable Mechanical Strain Gauge (DEMEC), as shown in Figure 6(c), instead of linear variable displacement transducers (LVDTs) mounted on the specimen. DEMEC has advantages of high accuracy and reliability; however, it could not provide continuous reading at increasing load. At least five, instead of the required minimum of three, values of deformation were obtained until the applied load was increased to approximately half of the estimated ultimate strength. The gauge length was determined to be 6 inches (approx. 152.4 mm). The DEMEC had a resolution of 1/10000 inch (approx. 2.54×10^{-3} mm).

4.2 Performance of individual reclaimed bricks

4.2.1 Reclaimed by saw cutting

Table 5 summarises the test results of perforated individual bricks for the saw cutting technique. Non-structural loadbearing frogged bricks of low strength and engineered perforated bricks of high strength were included in this study to cover bricks of different types and strengths. For each group of bricks (Figure 4), nine bricks were tested (the minimum is six according to BS EN 772-1:2011+A1:2015). The strengths of the new bricks were as expected. The results in Table 5 show that the reclaimed bricks without infill, and with infill, had slightly reduced dimensions compared with new bricks, due to slight extra cutting for cleaning. However, the maximum reductions, at 0.2%, 0.5% and 0.7% respective for length, width and depth are very small. Note that the average compressive strengths were converted to normalised compressive strength, f_b, according to BS EN 772-1:2011+A1:2015.

The reclaimed bricks without infill in core holes suffered a very small (0.12%) reduction in weight compared to new bricks. This change is negligible in masonry structural design. The reclaimed bricks, with the residual mortar not removed from core holes, had an increase in weight by 18.5% compared to the fresh bricks (due to a void rate of 19.68%). However, they achieved on average 39.62% increase in strength compared with fresh bricks (from 48.3 MPa to 68.0 MPa). This was expected because the residual mortar in core holes acted as confinement, which delayed the formation and progression of local crushing when the bricks were subjected to compression. This confinement could also change the mode of failure (Figure 7(a) and (b)); the developing of crack through the infilled mortar (Figure 7(b)) indicated that the mortar contributed to the load-carrying capacity.

Table 5 Summary of compressive tests of bricks reclaimed by saw cutting method

No.	Brick description	Perforated bricks, 3 cores			Frogged bricks		
		Av. weight (g)	Av, f_b (MPa)	SD	Av. weight (g)	Av. f_b (MPa)	SD
1	New bricks	2470.7	48.3	7.4	2423.5	7.3	1.1
2-1	Reclaimed bricks without mortar infilled	2467.6	52.5	12.2	2397.2	8.0	1.3
2-2	Reclaimed bricks with mortar infilled	2921.6	68.0	12.8	-	-	-

For the frogged bricks, the compressive strength of reclaimed frogged bricks also increased slightly compared to the new frogged bricks (Table 5). This could be attributed to the imperfection caused by the manufacturing process. Some of the new bricks had a slightly curved face, and grinding before the test was not able to guarantee flatness. Therefore, some of the new bricks exhibited a splitting failure mode (Figure 7(c)). Saw cutting helped to create a flat face and reduced the effect of geometrical imperfection (Figure 7(d)).

(a) **(b)** **(c)** **(d)**

Figure 7 Failure modes of bricks. (a) reclaimed perforated brick without infill, (b) reclaimed perforated brick with infill, (c) frogged new brick, (d) reclaimed frogged brick.

4.2.2 Reclaimed bricks by punching

For each type of bricks (Figure 5), a total of 10 bricks were tested according to BS EN 772-1:2011+A1:2015. Table 6 presents the average and standard deviation results for bricks reclaimed by punching. The results show that the reclaimed solid bricks had nearly identical compressive strength to the new solid bricks. For reclaimed perforated bricks, if the residual mortar in core holes was cleaned, the 3-hole bricks showed a slight reduction of 4.8% (from 63 MPa to 60 MPa) in compressive strength, whilst the 5-hole bricks showed a limited difference, compared with new bricks. If the residual mortar was kept in cores holes, the reclaimed 3-hole bricks increased by 3.2% (63 MPa to 65 MPa) in compressive strength compared with new bricks. Interestingly, the reclaimed 5-hole bricks with stronger mortar infilled (M12) showed an increase of 9.1%, whilst those with weaker mortar infilled (M4) exhibited a decrease of 4.5%, compared to new bricks. One plausible reason could be that punching initiated macroscopic fractures in bricks. Although only mortar was punched through, the reclaimed bricks also suffered from interlocking effect with mortar and thus might deteriorate. The 5-hole bricks were obviously having more interlocks with mortar therefore could be much more sensitive than the 3-hole bricks.

Overall, the reclaimed bricks showed a maximum reduction of 5% in strength compared with new bricks. For individual reclaimed bricks, such a limited reduction in compressive strength can be negligible.

Table 6 Summary of compressive tests of perforated and solid bricks reclaimed by punching method

No.	Brick description	Perforated bricks, 3 cores		Perforated bricks, 5 cores		Solid bricks	
		f_b (MPa)	SD	f_b (MPa)	SD	f_b (MPa)	SD
1	New bricks	63	3.9	44	2.6	30	2.6
2-1	Reclaimed bricks without mortar infilled	60	5.1	44	3.0	30	3.5
2-2	Reclaimed bricks with mortar (M4) infilled	65	10.2	42	3.6	-	-
2-3	Reclaimed bricks with mortar (M12) infilled	65	7.8	48	3.7	-	-

4.3 Performance of wallettes using reclaimed bricks

Figure 8 shows the failure modes of the four sets of tests of wallettes using reclaimed bricks by saw cutting (a)-(d) and by punching (e)-(f). They are similar showing vertical splitting with vertical cracks developing through the bricks and head joints.

(a) NFM12-1 (New frogged bricks)

(b) RFM12-1 (Reclaimed frogged bricks)

(c) NP3M12-3 (New perforated bricks)

(d) RP3M12-3 (Reclaimed perforated bricks)

(e) NP5M4-1 (New perforated bricks)

(f) RP5M4M12-2 (Reclaimed perforated bricks)

Figure 8 Failure modes of wallettes

4.3.1 Reclaimed by saw cutting

Table 7 shows the results of compressive tests of wallettes using 3-core perforated bricks and frogged bricks reclaimed by saw cutting. They appear to show reduced wallette mechanical properties using reclaimed bricks than new bricks. However, this reduction was not due to the reclaimed bricks. Rather, it was due to the mortar batch used with new bricks achieving much higher strengths than the nominal values of M12 and M4 which were similar to those used in the wallettes using reclaimed bricks. For example, the average mortar compressive strength for M12 mortar in the new perforated bricks was 54.42 MPa, compared to a value of 12.82 MPa used in the reclaimed perforated bricks. The reasons for the large difference in the average mortar compressive strengths of a nominal M12 mortar include: (1) different cement-to-water ratios; (2) different types of cement used for specimens RP3M12 and RFM12.

Table 7 Results of compressive tests of wallettes with bricks reclaimed by saw cutting method

No.	Description	Label	Mortar		Masonry	
			Mean flexural strength, $f_{m,f}$ (MPa)	Mean compressive strength, f_m (MPa)	(Mean) compressive strength, f (MPa)	(Mean) elastic modulus, E (GPa)
1-1	**New perforated** bricks, 3 cores, **M12** mortar	NP3M12-1	6 samples	12 samples	23.88	20.63
		NP3M12-2			29.98	19.67
		NP3M12-3			28.43	16.87
		Average	**5.15**	**54.42**	**27.43**	**19.06**
1-2	**Reclaimed perforated** bricks, 3 cores, **M12** mortar	RP3M12-1	9 samples	18 samples	21.02	10.33
		RP3M12-2			15.45	11.07
		RP3M12-3			20.29	13.45
		Average	**2.51**	**12.82**	**18.92**	**11.62**
2-1	**New perforated** bricks, 3 cores, **M4** mortar	NP3M4-1	6 samples	12 samples	23.65	15.46
		NP3M4-2			13.85	11.94
		NP3M4-3			17.53	12.67
		Average	**2.30**	**13.71**	**18.34**	**13.36**
2-2	**Reclaimed perforated** bricks, 3 cores, **M4** mortar	RP3M4-1	11 samples	22 samples	15.22	13.19
		RP3M4-2			14.98	13.90
		RP3M4-3			18.64	14.87
		Average	**2.17**	**7.95**	**16.28**	**13.99**
3-1	**New frogged** bricks, **M12** mortar	NFM12-1	6 samples	12 samples	5.50	2.16
		NFM12-2			5.70	2.45
		Average	**5.15**	**54.42**	**5.60**	**2.31**
3-2	**Reclaimed frogged** bricks, **M12** mortar	RFM12-1	9 samples	18 samples	6.35	2.95
		RFM12-2			4.25	2.13
		Average	**2.51**	**12.82**	**5.30**	**2.54**
4-1	**New frogged** bricks, **M4** mortar	NFM4-1	**2.30**	**13.71**	**4.14**	**-**

In order to substantiate the above statement, wallette compressive strengths were calculated according to BS EN 1996-1-1:2005+A1:2012, using the measured mortar strength in Table 7 (measured according to BS EN 1015-11:1999) and brick strength in Table 5. The formula is: $f_{\mathrm{k}} = K f_{\mathrm{b}}^{0.7} f_{\mathrm{m}}^{0.3}$, where f_{k} is the characteristic compressive strength of the masonry, in N/mm^2, K is a constant dependent on brick type, mortar type and volume of holes in bricks, for the perforated bricks used in the punching method K is equal to 0.45 and for the other bricks K is equal to 0.55, f_{b} is the normalised compressive strength of bricks, f_{m} is the compressive strength of mortar, in N/mm^2. The top subfigure in Figure 9 compares the calculation results with the test results for saw cutting method. It shows that that the calculated and test results are close. This confirms that the higher strengths of wallettes using new bricks is due to the very high mortar strength obtained. It also confirms the method of calculating the design strength of wallettes using new bricks can be applied to those using reclaimed bricks. Furthermore, if the mortar strength is identical (as in the calculations using nominal mortar strength values), the differences in strengths between new and reclaimed bricks have negligible effect on wallette strength.

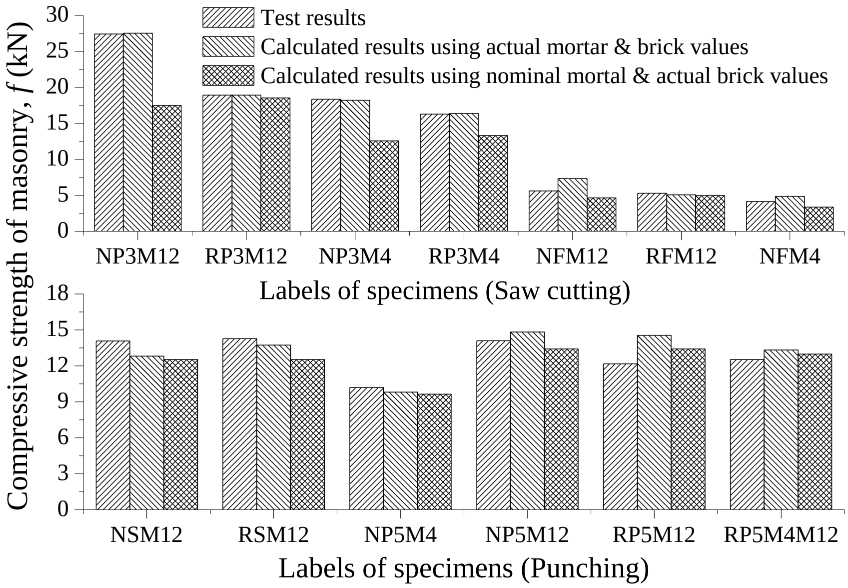


Figure 9 Comparison between calculated and measured compressive strength of wallettes

4.3.2 Reclaimed bricks by punching

Table 8 shows the results of compressive tests of wallettes using 5-core perforated bricks and solid bricks reclaimed by punching. The mechanical properties of wallettes using reclaimed bricks changed by -14% to 22% compared with those made of new bricks, e.g. series 1-1 and 1-2. Furthermore, by using mortar of a higher strength grade with reclaimed bricks, the wallettes were able to attain a higher compressive strength and elastic modulus (e.g. series 2-1 and 2-2; series 2-1 and 1-2). The measured wallette compressive strengths are generally close to the calculated compressive strengths, using either the actual mortar strength or the nominal strength (as shown in the bottom subfigure in Figure 9).

Table 8 Results of compressive tests of wallettes with bricks reclaimed by punching method

No.	Description	Label	Mortar	Masonry	
			Mean compressive strength, f_m (MPa)	(Mean) compressive strength, f (MPa)	(Mean) elastic modulus, E (GPa)
1-1	**New perforated** bricks, 5 cores, **M12** mortar	NP5M12-1	6 samples	14.70	5.723
		NP5M12-2		14.49	6.363
		NP5M12-3		13.11	5.066
		Average	**16.75**	**14.10**	**5.717**
1-2	**Reclaimed perforated** bricks, 5 cores without mortar infilled, **new M12** mortar for bed joints	RP5M12-1	6 samples	12.55	5.401
		RP5M12-2		10.31	5.445
		RP5M12-3		13.65	5.711
		Average	**15.73**	**12.17**	**5.519**
2-1	**New perforated** bricks, 5 cores, **M4** mortar	NP5M4-1	6 samples	10.13	4.241
		NP5M4-2		10.26	3.356
		Average	**4.25**	**10.19**	**3.799**
2-2	**Reclaimed perforated bricks**, 5 cores with old mortar infilled **(M4** mortar), **new M12** mortar for bed joints	RP5M4M12-1	6 samples	9.75	3.012
		RP5M4M12-2		13.56	4.558
		RP5M4M12-3		14.28	4.775
		Average	**4.14 (M4)** **13.08 (M12)**	**12.53**	**4.115**
3-1	**New solid** bricks, **M12** mortar	NSM12-1	6 samples	13.55	1.976
		NSM12-2		15.09	2.523
		NSM12-3		13.59	1.736
		Average	**12.89**	**14.08**	**2.078**
3-2	**Reclaimed solid** bricks, **M12** mortar	RSM12-1	6 samples	14.05	2.374
		RSM12-2		15.68	3.792
		RSM12-3		13.09	1.396
		Average	**16.24**	**14.28**	**2.521**

Note that all the findings are limited to masonry compressive strength only, other design strengths, e.g. shear strength, could be affected to a greater extent. Further research is ongoing.

5 Prospective availability of the new techniques

Decisions on whether bricks should be reclaimed and re-used are critically dependent on the economic and environmental benefits compared to new bricks. The prospective availability of these two techniques are highly linked with: (a) the cost of time and labour involvement in order to quantify their commercial viability along with the value-creation potential after remanufacturing; and (b) energy inputs as well as Global Warming Potential (GWP) in order to quantify their environmental impacts based on climate change inducing emissions. Climate change is not the only environmental impact associated with production and use of construction materials, but is a useful proxy for overall impact. . To help with making this evaluation, a performance analysis of the two reclamation techniques has been conducted in terms of the speed of reclaiming (number of reclaimed bricks per person per day PPPD) and the success rate, compared with the existing best rate. In addition, the energy consumption and GWP emissions during the reclaiming process have been preliminarily assessed and compared with the embodied energy and GWP emissions of manufacturing new bricks.

The recorded data for specimen type 3 (Figure 2(c)) was used to estimate these values for the saw-cutting method, because this unit would be reasonably close to the basic reclaimed brick panel that could be handled with a bench diamond saw. For masonry with mortar M12, the average lengths of time for cutting joints 1 and 2 (Figure 2(c)) were 41.15s and 40.11s respectively. For comparison, for M4 mortar, these were 38.36 s and 37.26 s respectively. Mortar strength had limited effect on the overall cutting speed. The average time for the head joints of M4 mortar (Figure 2c) was 4.36s, due to the limited length of the head joint. The power of the running saw was estimated using a current meter. The current was maintained to be roughly 10A, and this value was easily maintained for M12, whereas for M4 mortar, the required power was lower. Therefore, for reclaiming one brick, the overall saw cutting time would roughly be 25s per pair of bricks and the corresponding energy consumption would be 55 kJ assuming a current of 10 A (2400 W in power). The overall punching time would be 8s per pair of bricks with 360 kJ energy consumption at the current stage of development.

Table 9**Error! Reference source not found.** and Table 10 show the performance data using both saw cutting and punching techniques. Compared to the current best rate of manual reclamation of bricks bonded by lime-based mortar (2000 bricks per person per day), the current reclamation number of bricks with cement-based mortar using both techniques is lower. However, these values are based on manual processes developed in the laboratories which required a large amount (about 2 orders of magnitude compared to the actual cutting/punching time) of labour work for rig assembly, targeting and operation. Once the processes are automated, the rate of reclaiming bricks would be significantly higher.

Table 9 Comparison of time, rate of success for reclaiming method of bricks with cement-based mortar

Reclaiming method	Current Est. No. of bricks PPPD[a]	Rate of success
Saw-cutting	200	97.8% (178/182)

Punching	140	96.6 % (172/178)

[a]: estimated number of reclaimed brick per person per day

Reclaiming and reusing bricks is expected to decrease the overall environmental impacts of brick use by providing a stream of remanufactured materials to the market. Subsequently, for each reclaimed brick on the market, one less brick needs to be manufactured and its associated environmental impacts are avoided. In order to demonstrate the potential of the proposed reclaiming techniques in decreasing the environment impacts of bricks, the embedded impacts of production of bricks are compared to the reclaiming techniques. For this purpose, the life cycle GWP of a typical brick on the market is compared to the operational impacts of the reclaiming techniques. Electricity consumption of the machinery, that is considered to be the main contributor to the GWP impacts of reclaiming activities, is analysed by considering the GWP impact of UK electricity mix. Similarly, the energy balance of life cycle processes involved in production of bricks is compared to the operational energy consumption of reclaiming. Details of the comparison and the sources of data are described in Table 10 which indicates that, as expected, the embodied energy and embodied carbon of reclaimed bricks are only a very small fraction of those of manufacturing new bricks. The results indicate the reclaiming activities consume as little as 0.65% of the total embodied energy of brick manufacturing (Ecoinvent, 2017), thus showing high potential for improving energy and environment.

Table 10 Comparison of energy consumption and climate change inducing environmental emissions for brick manufacturing and reclamation

Brick type/Reclaiming method	Energy consumption (MJ/brick[a])	Emissions contributing to Global Warming Potential (g CO_2eq/brick[a])
Manufacture of new bricks (total embodied)	9.2[b]	757 [b]
Saw-cutting reclaiming (electricity at site)	0.06	0.54 [c]
Punching reclaiming (electricity at site)	0.36	3.22 [c]

[a]: *One brick is assumed to weigh 2.3 kg.*

[b]: *based on analysis of life cycle energy consumption and emissions, data obtained from Ecoinvent 3.4 for a typical clay brick of this size at the market and consequential allocation of life cycle processes- Cumulative Energy Demand and IPCC100a 2013 impact assessment methods applied respectively.*

[c]: *2014 UK grid mix based on electricity fed into the low voltage transmission network, data obtained from Ecoinvent 3.4.*

6 Conclusions

The research literature has previously concluded that it is not technically possible or practical to separate clay bricks form cement-based mortar without damaging the bricks. This paper presents two advanced methods of reclaiming bricks bonded by cement-based mortar and an assessment of the performance of the reclaimed bricks. These two reclaiming methods are saw cutting and punching. The assessment of performance focused on the mechanical properties of the reclaimed bricks and wallettes. The conclusions from this research are as follows: Reclaiming bricks bonded by cement-based mortar is technically possible. The reclaiming processes did not damage the bricks: The bricks reclaimed by both methods had similar visual and aesthetic appearance as new bricks. The reclaimed bricks had almost identical mechanical properties as new bricks. Wallettes made of reclaimed bricks had the same compressive strengths as those made of new bricks if the mortar strength is the same. The same method for calculating the design compressive strength of wallettes made of new bricks could be applied to those using reclaimed bricks. Measurement of the speed of separation and reclaim indicated that the techniques could be cost-effective. With automation, the reclaiming methods could be made more efficient and cost-effective.

The reclamation process using both reclaiming methods had significantly lower energy, and carbon requirements (<1%) relative to new bricks and therefore showed high potential to mitigate greenhouse gas emissions and to make a great contribution to future urban mining, circular economy building systems and mitigating climate change.

Having shown the feasibility of separating bricks from cement-based mortar without damage and the potential economic and environmental benefits of brick reuse in Section 5, the next step of the analysis is to conduct a holistic assessment of production of new bricks compared to the activities involved in reclamation in full-scale wall demolition to understand the full scope of the environmental impacts of the proposed techniques. Thus, a full Life Cycle Assessment (LCA) is proposed to be performed in order to encompass the entire activities that are involved in operationalising these techniques at economic scale. This, along with economic and technical assessments, can better indicate the potential of reclaiming and reusing bricks. Furthermore, the estimation of the number of bricks is planned in different full-scale wall settings in different buildings as the basis for 'urban mining'. City scale 3 and 4D models have been developed to enable a full assessment of the potential economic and environmental impacts from developing field scale brick reclaim systems.

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Declarations of competing interest

None.

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