Reclaimed Clay Bricks: Challenges & Opportunities with their Implementation and Design

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AUTHOR DECLARATION

I hereby declare that I am the sole author of this thesis and that, to the best of my knowledge, this thesis contains no material previously published by any other person except where due acknowledgement is given. All data and research presented in the thesis are accurate and truthful to the best of my knowledge. There is no provision surrounding human interests in the research and the researcher is independent from the study.

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ABSTRACT

This thesis studies the implementation of reclaimed bricks back into structural environments, exploring the possibility of introducing bricks which have already served as a building component in the past as a load-bearing element in new or refurbished buildings and structures. The idea of reusing bricks is only possible due to their unique properties of high durability, reliability, compressive strength, and low cost which make them very popular as a load-bearing option. This allows structures-built thousands of years ago to remain standing today. However, most bricks never reach their full potential design life which results in poor material efficiency and unnecessary waste.

This study used laboratory testing to compare the properties which are the greatest indicators of brick performance, compressive strength, and water absorption. It compares reclaimed bricks and modern manufactured virgin bricks of similar shape, size, and material. The results show that the new brick samples outperformed in both tests showing the reclaimed sample set had a poorer and more inconsistent result pattern which, as discussed in the literature review, confirms the biggest concern when designing with reclaimed bricks… uncertainty.

Keywords: Reuse, Reclamation, Brick, Material, Strength, Sustainability, Compression,

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1 INTRODUCTION & OBJECTIVES

1.1 BACKGROUND

Bricks have, quite literally, been the building blocks of society since their creation. With the first concepts of bricks stretching as far back as 7500 BC in East and South Asia [1]. Since then, they have become one of the most popular and stable building materials used in all aspects of civilisation. Roads, bridges, dams, buildings, and sewerage systems have all incorporated the bricks to provide robustness and longevity. However, it is not solely bricks that add rigidity and strength to a building. Rows and rows of brick, joined and set in place using mortars, is what gives its well-known high stiffness and longevity.

The development of bricks from past to present has been profound, with primal bricks often rougher, less consistent and using a greater amount of raw material. More recently, bricks have been manufactured using high-quality materials and in controlled environments which has resulted in a stronger structure and resource-efficient design. However, the process of creating bricks has always maintained its detrimental impact on the environment. The forever-adopted concept of single-use bricks is a waste of resources and energy. The construction industry, by its very nature, is a massive user of natural resources. The manufacturing of all building materials beings with raw material extraction from the ground, where they are then processed into highly efficient engineered products suitable for all types of application. However, with growing concerns of the industries significant carbon output and the limited nature of natural resources, there has never been more pressure on the sector to change out of wasteful, ancient practices and into the era of resource efficiency and a green construction revolution. Hence an opportunity has arisen for the construction industry to prove it is serious about its sustainability agenda with the idea of re-using bricks. Sustainability in construction, by its definition, is ‘to meet the needs of the present without compromising the ability of future generations to meet their own needs’ [2]. The idea of brick reusability represents a fascinating possibility at a time when the cost of dumping construction waste is on the rise. With the number of landfill sites around major cities in the world on the decrease, so too is the allowed volume and frequency of dumping, the cost of purely unloading construction waste and forgetting about it is becoming ever more expensive and difficult. In the United Kingdom (UK), this problem has become even more prevalent due to the introduction of a landfill tax by the government. The standard rate in 2023, is £102.10 per tonne [3]. This significant cost forces many contractors and heavy wasters to reconsider their actions and allow for the adoption of sustainable practices to become a much more feasible option.

Due to the growing concerns over the environmental implications of raw material extraction and the continued rise in demand, the construction industry must be open and ready to the idea of reusable brick units. The term re-usability in construction is often overlooked in favor of recycling. The concept of construction waste recycling has been the biggest focus of the industry in the past decade, yet little attention has been given to the much more environmentally friendly practice of reuse. The recycling of bricks is more damaging than the simple and straightforward idea of reuse as it involves breaking down the units into powder or small chunks using massive, energy intensive crushing machines. The material is then reprocessed and repurposed as either a sand or aggregate substitute. However, reusing bricks is not all without its faults. Historically, the brick industry has been somewhat cautious about promoting the reuse of brick as there are many serious practical barriers which must be addressed. One of the biggest hurdles has been the lack of strict grading rules for reused materials in a structural application, in particular a lack of guidance for measuring the safety and strength of so-called 'one-use' materials. Civil engineers and designers alike are the most risk-averse people you will find, if there is any identified risk, they will try their hardest to minimise it or eliminate it entirely. Hence why this topic is complex.

1.2 Material passports & circular economy principles

The concept of so called 'material passports' may be a welcomed solution to the wastefulness of materials in the construction industry. Material passports are a specific type of passport developed to collect data on a materials manufacture, history, current and even future uses. Giving the materials their best possible chance at shining through the dark cloud of uncertainty that concerns the designers and engineers. This concept, developed by the 'Building As Material Banks (BAMB) initiative, can also accelerate the industry into developing circular economy principles [4]. Which minimise waste by efficiently utilising materials. A diagram of current linear economy practices against circular economy principles can be seen in Figure 1 below.

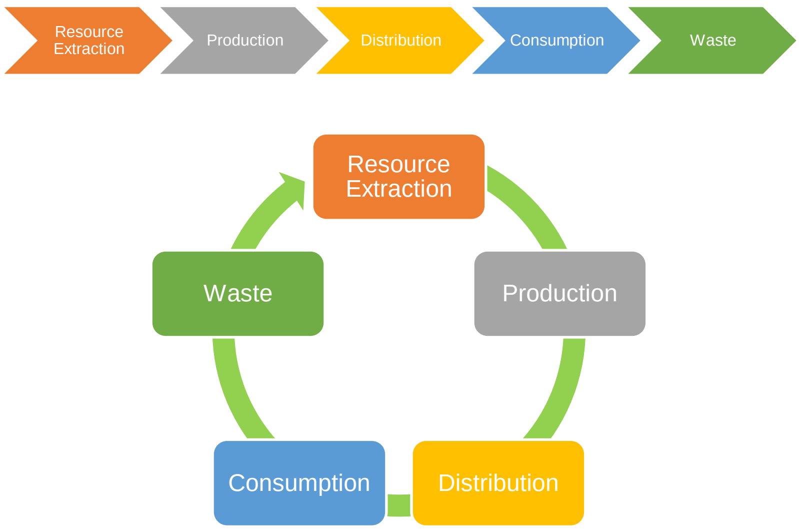

Figure 1 - Current linear economy (top) against circular economy approach (bottom)

Old fashioned construction followed a linear system, where it was left open ended and under regulated which allowed for high costs and high wastage, which churned profits and limited the potential for the industry to grow [5]. More recently, the transition to a circular approach has accelerated due to the increased savings and benefits on both the business front and the environment. When speaking of the environment, and the impact the industry has, it is relevant to discuss the idea of embodied carbon. Put simply, embodied carbon is the trail of emissions related to the extraction, manufacturing, and transportation of materials as well as the emissions caused by the installation and construction of these materials on-site. As seen below in *Table 1*, brick has a modest embodied carbon content in comparison to other building materials, with a typical cubic metre having 357 kg CO_2, mostly generated from the extraction of raw materials from quarries, and the process involved in the manufacturing such as shaping and firing. However, if you were to compare the embodied carbon of brick with concrete, you would find on average that concrete has ten times the associated carbon emissions of brick, averaging around 3,507 kg of CO_2 [6]. Despite this comparison, brick still produces 40% more embodied emissions compared to the same volume of timber [7]. By purely re-using a building material, with no-reprocessing or machine strengthening, it can save almost all its embodied carbon impacts and preserves its economic value. For each reuse, a material will prolong its lifetime and in doing so can become more material efficient for the same amount of carbon. This concept is the greatest opportunity to increase the environmental efficiency of the construction industry.

Material	**Embodied Carbon (kgCO2/Tonne)**	**Lifespan**
Brick	357 [8]	150+ years [9]
Steel	2800 [10]	100 + years [11]
Concrete	3507 [6]	~ 100 years [12]
Cross-Laminated-Timber (CLT)	250 [13]	~100 years [14]

Table 1 - Common Building Material embodied carbon and lifespan.

1.3 DOMESTIC BRICK SUPPLY

Going back in time to the height of the European Industrial Revolution, the continent was making tens of billions of bricks every year to build commercial, industrial, and even some of the residential buildings that remain today. At that time, Britain was one of the biggest consumers of brick products and was able to keep up with its booming demand as a result of the nearly fifteen-hundred brickworks across Britain [15]. Now, because of both Brexit, COVID-19 and inflation we are seeing the lowest levels of clay brick stocks for almost 30 years. Approximately 1.9 billion bricks are manufactured in the UK each year, with an overall demand for 2.5 billion [16]. Creating a shortfall in the supply of bricks throughout the country [17] and as a result many small builds and self-builds are making a beeline for reclaimed stocks. The scarcity of bricks is only set to increase, with development of ‘new build’ homes ramping up throughout the UK, and with increased competition from foreign brick suppliers putting domestic manufacturers out of business, the industry will fall short of readily available stocks. The reliance on brick imports has risen sharply [18] [16]. So, why do we continue to adopt the single-use ideology? China, one of the UK’s brick lifelines, is the world leading exporter of bricks, producing two-thirds of the worlds supply and generating an estimated $7.51 billion in sales year on year [19]. These bricks are transported via slow, dirty, and environmentally destructive cargo vessels across the world. Where they dock at port and are unloaded onto trucks, trains and often further cargo vessels which only continue the milage from its origin location. All these associated emissions tie into its embodied carbon, which for 27 tonnes of bricks (around 8 thousand units), enough for a small single-storey home, shipped from the port of Shanghai, China to Thames port London, has emissions of just under 2000 kg of CO_2 on transport alone [20]. Which, if sourced domestically could reduce the embodied carbon associated with transportation dramatically.

Another challenge, perhaps greater in complexity is the careful deconstruction of existing buildings. The extended time and extreme demands on manual labour is seen as extremely unfavourable to a demolition contractor looking to keep costs, and hence time, to a minimum. Sweeping new regulation changes, an increase in skilled workers and the use of modern and efficient demolition practices can remove the traditional construction ‘take-make-waste’ model and reduce the financial and practical burden placed on the contractor. meaning the building will not have to be taken down ‘brick-by-brick’. However, problems stem from the design of each-and-every building set for demolition. By nature, these buildings were not designed for deconstruction, they are designed for their application. Whether that be a school built to last sixty years or a nuclear power station build to the highest operational safety and security. The focus of design is the ability for the structure to last because that is what the client wants. Hence a problem surfaces; who is going to pay for the implementation of sustainable measures? The client does not care if a building can be efficiently demolished, as they see no benefit, the contractor does not want to take on additional cost as the client will seek the best value for money during procurement of the project, where competition is fierce.

1.4 RESEARCH AIMS & OBJECTIVES

This research focuses on fired clay bricks, which are the most traditional and widespread brick found throughout the world [21] . Even with this statistic, their application when it comes to reuse is currently limited, being used for only aesthetic and architectural value. If the reuse of bricks into load bearing environments is successful, it can allow the industry to not only fulfil its environmental and sustainable targets, but also open new markets within the industry that create jobs and increase industry value.

The objective of the research is to determine the suitability of reclaimed bricks back into structural environments. A bricks compressive strength and water absorption categorisation are two of the major physical properties of bricks and give the most effective predict of its ability to resist cracking and thus determine suitability for reuse. This study compares the result of these two tests on both reclaimed bricks and virgin bricks, evaluating the results to produce an evidence-based answer to the question. The research will also uncover why reused materials are not preferred by contractors and designers throughout the built environment, assessing concerns and barriers that limit their implementation. It will also shine light onto the current UK Government goals when it comes to the reuse of construction materials, understanding and evaluating the literature on the subject.

The document follows a standard format, the next chapter investigates the current literature covering the main topics of the subject. With both advantages and disadvantages of the use of reclaimed masonry explored, highlighting the main concerns in its implementation. The literature review provides a balanced outlook on the matter. From there, the methodology of the research is explained, with the procedures for all the testing summarised in detail. The raw data from the tests are then analysed to provide an observable answer to the question of whether reclaimed bricks are physically suitable for reintroduction into real world, load-bearing structures. It will determine the physical property restraints of the reclaimed bricks and hence the limitations in design using these units. The discussion explores how the research conducted could have been improved in areas such as accuracy and relevancy as well as what the analysis of the results means and how it may affect the subject.

2 LITERATURE REVIEW

2.1 INTRODUCTION

This literature review aims to provide a summary of the main gains and limitations met in the implementation of reclaimed bricks in structural environments. The outline of this section begins with current attitudes towards the reuse of building materials including bricks. The opportunities for reclaimed bricks are explored, considering the environmental and economic benefits of the concept. Then looking at the prospect of preserving the historical and architectural value of structures using reclaimed bricks. The second half of the chapter will explore the limitations of reclaimed bricks including the current physical and legislative obstacles in the application of reused bricks.

2.1.1 The Need to Re-use Bricks

The construction industry has shifted its focus towards sustainability in the past decade, emphasizing the need for cleaner and greener building practices, and overall reducing its environmental impact. In the UK alone, the construction industry creates 18% of all emissions in the UK [22]. With construction the backbone of society, its importance is undisputed. However, due to the emerging climate crisis, construction must play its part in achieving environmental targets set out by governments both at home and around the globe. The reuse of building materials is an easy and straightforward area that the construction industry can use to meet emission goals. A study into construction and demolition waste found that re-using was the most sustainable choice for construction waste management, not only for saving landfill volumes, but majorly the reduction of greenhouse gas emissions [23].

2.1.2 Defining & Understanding Attitudes

Re-use is an often-forgotten term in waste management hierarchies. Recycling is a much more widely known and used method both by companies and consumers. Re-use improves material efficiency overall and is the second-best choice after waste prevention to reduce resource consumption and greenhouse gas emissions worldwide [24]. This idea ultimately diverts unnecessary demolition waste from landfill and offers new lives for bricks and building materials overall. However, concerns are arising industry-wide about the suitability of building materials in new structural applications. The Brick Institute of America discouraged the use of salvaged brick in structural settings due to concerns over damage caused by the separation of mortar during the reclamation process, which affects performance [25]. Although old, it is the current technical document used by the association. In more recent times, and with the acknowledgement of the climate crisis, opinions have shifted to the recognition and promotion of re-using construction materials. The Brick Development Association stated that they encourage the re-use of bricks provided users can evaluate fitness for purpose in the chosen environment. [26]. While these associations have no direct influence, their recommendations help gather attention and increase awareness.

Awareness around the issue is becoming more and more mainstream. At an architectural conference in June 2019, Duncan Baker-Brown a sustainable designer emphasised the need to use the resource and material that is already above ground and how the need for change is critical [27]. Since the speech, the concept has gained traction, being recognised by industry leading companies and governments worldwide. In Scotland, a government funded campaign "zero Waste Scotland" promotes on its website the reuse of construction building materials [28].

2.2 OPPORTUNITIES FOR RE-USED BRICKS

2.2.1 Environmental

One of the biggest benefits of brick reclamation is the undisputed raw material conservation. The production of new bricks requires the extraction and processing of raw, virgin materials from the ground, which can negatively impact the environment due to the associated greenhouse gas emission. To compare that with reclaimed bricks, where the raw material has already been extracted and processed, the environmental impact can be lessened dramatically. This was investigated in a study conducted in Norway. It found that the reuse of construction products has the potential to reduce resource consumption by 20% in the Nordic construction sector resulting in greenhouse gas emissions savings of approximately 900,000 tons of CO2 equivalents [29]. A research paper by Marwa Dabaieh [30] revealed similar findings. It was found that energy consumption during manufacturing contributes massively to a building's life cycle energy demands, and carbon emissions could be significantly reduced by lowering the energy required to manufacture building material. Therefore, saying that the energy saved by reusing bricks can massively reduce the associated embodied carbon from the bricks as the life cycle of the material is increased.

Elementary economics tells us the supply of reused bricks reduces the demand for new bricks. Thereby reducing the associated environmental impacts. Additionally, the transportation of reused bricks from their original location to the construction site is often more energy-efficient than the transportation of new bricks from a manufacturing plant. This was evident in a study conducted that found the environmental impact of reclaiming brick was only a small fraction of the potential impact of primary production. It concluded it would be possible to transport the bricks a distance of 15,000- 20,000 km before the CO2 emissions would equate to that of the production and manufacturing of new bricks with virgin materials [31]. Making the point that there are tremendous environmental savings to be made by reusing bricks and that there is no reason why the normalised end-of-building life demolition 'waste' can't become material and product banks for future builds.

2.2.2 Economical

In order for the re-use of bricks to be taken seriously, it must become economically sustainable. While the idea of re-using building materials is predominantly sourced around the industry's sustainability and environmental goals, there is a discussion to be had in to the often-overseen economic benefits. A project backed by the European Union investigated the economic opportunities relating to regenerative buildings, the study found that there was huge market potential for reclaimed and remanufactured materials [32]. The study looked at the opportunity to create new jobs across Europe and the increasing market for reusable materials across the continent. Momentum stemmed from the European Green Deal which announced a wave of green initiatives aiming to implement circular economy principles into construction sectors. Ultimately promoting and pressuring for sustainable and circular use of materials [33]. This circular economy approach aims to keep resources in use for as long as safely possible, then recovering and regenerating products and materials. Ensuring maximum potential is extracted from every material. With these measures in place, the reuse of materials would become much more mainstream and simpler to implement. [34]

The simple fact of the economics of reused bricks is that they are typically less expensive to produce than new bricks, as they have already been shaped, fired and hardened which makes them a much more cost-effective solution for construction projects. This is especially the case where new bricks are not locally available or are in high demand. Since Brexit in 2020, there has been an increasing shortage of bricks in the UK due to tiring import paperwork, inflated transportation costs and lack of labor. Creating the ideal opportunity for bricks to be salvaged, cleaned, and prepared for reuse [35].

2.2.3 Preservation of Historical / Architectural Value

Reclaimed bricks are most sought after for use in restoration projects. In conservation areas, the use of reclaimed bricks may be specified to ensure that the structure fits into its surroundings. This is due to their distinct appearance and texture that adds visual character and charm to a building [36]. However, in recent times manufacturers have developed new brick products that look as though they have been reclaimed with features such as chips, paint remnants and random dark stains. These bricks not only look authentic but comply with current standards [25] which are much more favourable in projects due to the minimised uncertainty surrounding their quality and strength. It appears the market for reclaimed bricks cannot be set on historical and architectural value alone, as their appearance and characteristics can be mimicked in the manufacturing process of new bricks. Other principles discussed in this document such as environmental and economical will have to contribute if the idea is to be successful.

2.3 CHALLENGES ASSOCIATED WITH REUSING BRICKS

2.3.1 Consistency of brick Properties: Strength & Wear

One of the greatest hurdles when it comes to construction waste re-use is the lack of confidence in material quality. Reducing overall demand and popularity of the concept. An analysis of the challenges presented with reusing bricks and other materials found there was a reluctance to adopt due to the increased risk involved. Designers perceived additional risks by specifying components with less predictable strength characteristics. The paper highlighted a case study where the client was willing to take on this risk for ideological reasons, but this will not be the case in most projects. In many cases, non-uniform specifications prevent or inhibit the use of reused components for reasons of reducing liability in structural performance [37].

The strength, or lack of strength, in reused bricks, is the main challenge when it comes to design. The overall strength and suitability of reclaimed bricks are uncertain, additional testing and evaluation measures are usually put in place to ensure standards and specifications are met. The advantage of specifying new clay bricks is that they are plentiful in supply and manufactured to well-established UK and European Standards. [25]

Another important consideration when reusing bricks is the wear inflicted during their demolition and reprocessing. Bricks deteriorate over time with weathering actions causing cracking, chips, and fissures which compromise structural integrity. A survey conducted by 'FutuREuse' found that the quality of reclaimed bricks tends to be poor, and the survey found only 75% of sold bricks had at least one clean end and one clean face. Only 5% of the sold bricks have a frost-resistance guarantee [31]. The uncertainty around the wear of reclaimed bricks can be, in part, due to the unknown conditions each brick was subjected to. Such as weather conditions or pollutants which pose major challenges due to weakened or contaminated bricks.

Perhaps the most important parameter in the suitability of brick reuse is the connection method between each brick. Historically, lime-based mortars were the predominant choice when it came to brick connections [38]. Due to the bricks being fired at a much lower temperature, it causes them to be softer and therefore designed to be permeable so they can absorb moisture then release it. Comparatively, modern bricks are fired at much higher temperatures causing the bricks to harden and become more watertight as a result [38]. This was proven in a scientific study into the influence of cement in lime mortars, which stated that the amount of cement in mortar increases its mechanical strength and its resistance to soluble salts and frost resistance [39]. Therefore, lime-based mortars are designed to be more breathable, flexible, and porous, meaning that when it comes to reclamation of structures using lime-based mortars, it requires much lighter and less forceful separation of bricks, causing less damage overall [40]. Portland cement-based mortars were designed to be robust. As this mortar was designed to be paired with a more watertight brick, it was produced as non-breathable and non-porous. It is a quick-setting and cheap mortar that has a much stronger structure to meet modern building practices. As a result, the reclamation process for structures using cement mortars is challenging. As the bond between brick and mortar is very strong, it requires a great deal of force to break, which most often causes damage to the brick and voiding is for future use. This presents a real challenge in the reclamation of bricks from structures post 19-century, when sand-cement based mortars began to be introduced [41]. Damage and lack of efficiency in the method of separation in Portland cement bonds makes brick reclamation a niche market that has a low processing speed causing operating costs to increase and therefore low uptake.

2.3.2 Current Building Practice – The need for aligned Demolition and Recycling Practices

At a time when resource efficiency is a top priority on the European Agenda, Reuse is still in its early stage in the UK and around the globe, and only a handful of test pilots have been carried out. Current UK legislation relating to the minimization of construction waste has failed. The implementation of the Landfill Tax (£102.10 per ton April 2023), the Aggregates Levy (£2 per ton) and the Site Waste Management Plan does not appear to have seriously reduced the amount of waste production as intended [42]. Without increased fiscal measures or legislation in the future, the idea of closed-loop construction can be forgotten about. Standard construction and demolition practices focus on the fastest, easiest and most economical way to get the job done [37].

However, the outlook overall looks promising, The UK Government has remained committed to increasing taxation on landfill usage to encourage alternative methods of waste disposal. Not only have they increased taxes on the disposal of old bricks, but there will also be rises in the taxes on the extraction processes involved in the production of new bricks. The increased production cost to 'offset' the extraction tax is passed on to the cost of newly manufactured bricks, giving reclaimed bricks a greater saving potential [31].

2.3.3 Design for Deconstruction (DfD)

As it stands there is very little difference between the financial cost associated with disposing of demolition waste and the labor associated with demolishing a structure 'brick-by-brick'. Hence brick reclamation is currently only practiced at small yards and most bricks used in construction are bricks manufactured by large companies. A study conducted into the adoption of controlled demolition found that contractors are only likely to consider the value of bricks in a building if it was bound using old soft lime mortars, which are easier to remove as discussed before. If the mortar is decided to be weak enough, it is preferable that the building be demolished brick-by-brick, ensuring each brick is cleaned and placed to ensure quality. However more conventionally, the mortar-brick bond is too strong, resulting in the wall being mechanically pushed over. Which forces the brick bonds to loosen, allowing them to be picked. This however can cause damage to some of the bricks and render them unsuitable for reclamation [24].

A study from 2018 that investigated design for deconstruction and how it affects the design process found that due to the lack of tools available to support the design for deconstruction ambition, uptake has been restricted [43]. The main issue in DfD's implementation was the lack of legislation promoting and encouraging the concept. As well as cost and time constraints which ultimately landed on the client, who seen it as more of a hindrance than opportunity. The same study explained that different building materials have varying potential for deconstruction. And that having the knowledge of the advantages and shortcomings of these materials was essential for the design team, so they could determine a building's full potential. [44]

To summarise, the literature on the reuse of bricks provides balanced arguments for and against its implementation. The overall literature on structural applications is negative, while more recent legislative and theoretical literature provides a more compelling case. Further, the environmental and economic advantages are incredibly rewarding and encouraging, there is still an underlying problem that plagues the implementation of reused bricks for load-bearing conditions. That is the uncertainty surrounding wear and structural performance that stems from disruptive demolition practices and a lack of constructive legislation. With these issues addressed, the potential for the construction industry to be serious about its sustainability targets can surface.

3 METHODOLOGY

3.1 PHILOSOPHY OF RESEARCH

The main objectives of the research will be met through quantitative methods, whereby destructive and non-destructive laboratory testing will be the primary data collection method. The experiments conducted follow an epistemological approach, where only what is known to be true can be used to make conclusions. It was deemed most appropriate to use experimental data in this research as conclusions on the reusability of bricks would be difficult to reach purely from theoretical data, and therefore physical testing must be used to determine the difference in properties between reused and new bricks.

It is most appropriate to focus the research to the approach of positivism [45]. The positivism philosophy finds the answer to the research from experimental testing of a main objective, which is to make direct comparisons of compressive and weatherability properties of reclaimed bricks against new bricks, to ultimately test their suitability for reuse. It is important that the study into reclaimed bricks is formed around fact. There is no provision surrounding human interests in the research and the researcher is independent from the study, meaning the conclusion cannot be directed or structured to ensure a targeted outcome.

3.2 RESEARCH APPROACH

For the application of this research, an inductive research approach must be adopted to recognise patterns and behaviours of the two sample sets. These patterns must come from specific observations of the tests and the data collected. General conclusions are then gathered based on the test results. It is hypothesised that the new bricks will outperform, on average, the reclaimed bricks in both the determination of water absorption [46] and compressive strength [47]. This is hypothesised due to advancements in brick manufacturing quality and standardisation and furthered by the potential of age-related fatigue on the reclaimed samples.

The water absorption test will be conducted as water absorption is a fundamental property in masonry. Water absorption can affect the quality of the brick itself and can weaken the strong bond between the brick and mortar in masonry structures- resulting in a reduction in strength properties. Data extracted from the water absorption test will be used to indicate the durability properties of the refurbished and new bricks. It will produce an understanding of the quality of each brick, its rate of absorption and its behaviour in weathering conditions. The reclaimed bricks can then be classified in terms of its water absorption percentage which will ultimately determine its suitability for reuse.

The justification of the crushing compressive strength test was to understand and validate the samples suitability for construction. Brick is generally used in load-bearing masonry walls, columns, and footings- in which compression is the underlying force, therefore it is important to gauge the strength of bricks in compression if this is the primary force they will be subjected to in reintroduction. From the raw data gathered, the force per unit area (pressure) was calculated from the force value at which the sample failed. From this value, the samples can be classified as an average compressive strength, assuming they meet a minimum pressure. A statement can then be made as to whether the samples meet the required strength and if they were suitable in a load-bearing environment [47] [48]

3.3 SAMPLE BACKGROUND & PREPARATION

The ten samples of reclaimed brick were sourced from a former industrial colliery in Prestonpans, East Lothian. The Prestongrange site was first established in the twelfth century and boasted mining, a brickwork and pottery [49]. At its peak the brickworks shaped and fired 225,000 bricks per week and around 6,000 metric tonnes of bricks, fireclay pipes and fittings per year. The management, and site layout of the works changed over its industrial lifespan as seen in *Appendix A-B*. However after the 1960s the site began to turn down, with the colliery closing in 1962, and then the brickworks in 1975 [50] [51]. The National Mining Museum was formally launched at Prestongrange on 28th September 1984 [52]. The reclaimed bricks were manufactured at the Prestongrange site and were fired in a Hoffman Continuous Kiln [53] that remains as a museum exhibit. The reclaimed bricks were collected from the same location, a rubble pile located next to the Hoffman continuous kiln *[Appendix C-E]* located on the southwest corner of the Prestongrange site. Many of the bricks in the pile had been greatly damaged, and the majority had been halved. *[appendix F].* Permission was granted by East Lothian Council, who now operate the museum, to use the bricks under the assurance that none would be taken from active structures, behind fencing or from any current application. It was also stipulated that the brick pieces be returned after testing.

From historical data published by the John Gray Centre [51], it can be confidently said that the reclaimed sample set are at least fifty years old. However, due to mortar-brick bonds that were prevalent on most of the set, it can be further assumed that the bricks come from a previous structure which may date them back to the early stages of the colliery or during its last renovation, which would estimate them as over one-hundred years old [54]. A random array of bricks were chosen from the site, ranging in shape, size, and general appearance. This sample selection method was used to ensure transparency of the results and to eliminate any confirmation bias that could change the outcome of the study. The reclaimed set of bricks each had varying severities of damage and estimated age, with the majority showing heavily eroded edges and undefined frog bed areas. The full extent of the damage of each brick can be seen in the appendix, *Appendix G-Y.*

Before commencing testing, the reclaimed brick samples were first cleaned using a steel wire brush to remove any loose mortar, vegetation and dirt that was present on the faces and that filled the voids. For tougher mortar-brick bonds, which was present in many of the frog faces, a chisel and hammer were used. The new bricks were not cleaned as they had no signs of dirt or vegetation.

The determination of water absorption of clay masonry units by cold water absorption was the first test conducted, as the compressive test took all the samples to failure. The standard sets out the minimum number of specimens that can be tested as six, for the research there were a total of twenty bricks tested, ten reclaimed and ten new. The samples were first dried in an oven at 105°C ± 5°C for twenty-four hours to achieve a dry mass. After cooling to an ambient temperature, the mass of the samples was recorded using an AJ-6200E precision balance which meets the required tolerance of 0.01g. [55]*[appendix Y]*

To determine the compressive strength of the bricks, samples were prepared and conditioned in accordance with BS EN 772-1:2011+A1:2015 Annex B – Surface preparation and conditioning of units *[Appendix Z]* [47]. Before testing could commence, the specimens were conditioned to the dry oven method of preparation (7.3.3). Where they were dried at 105°C ± 5°C for twenty-four hours until a dry mass was achieved to ensure that any remaining moisture from the cold-water absorption test was removed and to ensure the results were valid. The samples were then cooled again to the ambient temperature of the room which was measured to be 19°C. The mass of the specimen before and after drying were recorded.

3.3.1 Procedure for dimensions and dry density

For the calculation of the brick dimensions according to BS EN 772-16:2011 [56], digital callipers were used to measure the width *(w_u)* and the height *(h_u)* of each of the brick units. For the measurement of the length *(l_u)* a steel rule was used as the callipers had a maximum measurement of 150mm. Each measurement was taken three times at different sections of the brick, to obtain the absolute dimensions of the units. Figure 2 below gives an illustration of where the measurements were taken on each sample. The callipers had an accuracy of 0.01mm whilst the steel rule could only be observed to 0.1mm. the measurements were taken on each unit and variance is calculated.

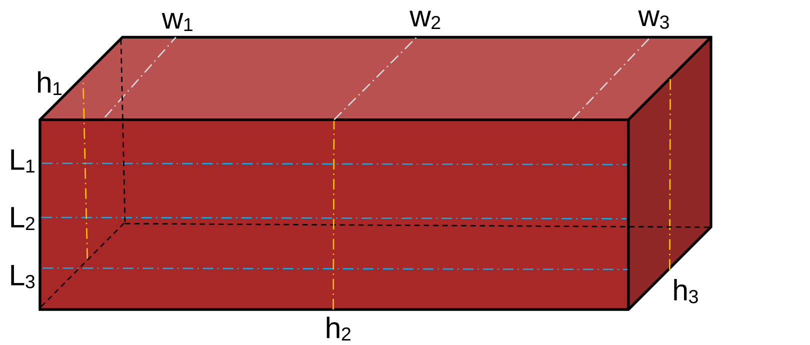

Figure 2 - Illustration of Absolute Dimensions

For the determination of net dry density according to BS EN772-13:2000 [57], the samples were dried at 105°C in an oven for 24 hours before being allowed to cool to ambient temperature. The dry mass ($m_{dry,u}$) was then taken. The measured dimensions of the units were then used to calculate the volume and *Equation 1* below was used for the determination of the net dry density of the masonry unit ($\rho_{n,u}$):

$$\rho_{n,u} = \frac{m_{dry,u}}{V_{n,u}} \times 10^6 (kg/m^3) \qquad (1)$$

Equation 1 - Net dry density of masonry units

Where $m_{dry,u}$ is the dry mass of the unit (g) and $V_{n,u}$ is the net volume of the unit (mm^3). For densities over 1000kg/m^3, the density is expressed to the nearest 10 kg/m^3 as per the instructions set out in the standard. [57]

3.3.2 Procedure for water absorption test

The water absorption of the brick units was determined using BS EN772-21 [46]. Firstly, the dry mass measured in the determination of net dry density was collected. Then the samples were placed into a filled water tank, where they were positioned so that they were fully submerged in the water and that a maximum of one face was in contact with the tank. The water used for the test was cold mains water, it had not been heated or treated as part of the testing procedure. The units were then removed from the tank, one at a time, after 24 h ± 0.5 h. they were then wiped with a damp cloth to ensure that surface water was removed. The samples were then weighed, and their saturated mass was recorded. Equation 2 below was used to then calculate the percentage of moisture in each specimen as a result of the cold-water absorption.

$$W_s = \frac{M_s - M_d}{M_d} \times 100 \quad \% \qquad (2)$$

Equation 2 - Masonry unit water absorption formula

3.3.3 Procedure for brick compressive test

The following procedure applied for all bricks, both reclaimed set and new set and is conducted in accordance with BS EN 772-1:2011+A1:2015 [47]. As per the procedure of the test, two plywood cut outs were placed in between the brick and the plates of the machine at both the top and bottom beds. The plywood was centred on the faces to ensure that there was an even overlap of plywood on all edges to confirm a uniform distribution of load onto the brick, shown in Figure 3. The samples were inserted, centrally, into the seated plate within the Avery 1000 kN Hydraulic compressive testing machine, seen in Figure 4 below.

Figure 3 - Image of prepared new sample being placed into testing machine

Figure 4 - Avery analogue compressive testing machine used for the reclaimed bricks

As per the guidelines set out in the standard, bricks which had frogs were positioned 'frog-up' which applied entirely to the reclaimed sample set. The gap between the brick and the compressive arm of the machine was closed, and each set of brick were compressed at a calculated loading rate, which was determined using the expected failure load of each brick and the average bed area of each set. The loading rates are shown in the table below, Table 2. *[appendix AA]*

Brick set	Expected compressive strength (N/mm^2)	Loading rate (N/mm^2)/s	Loading rate (kN/s)
Reclaimed	11 – 20	0.15	4
New	41 – 80	0.6	13

Table 2 - table of calculated loading rates

The selection of expected compressive strength *[appendix AB]* had to be carefully selected to ensure that failure of the specimens occurred in no less than one minute. This was a consideration given in the guidelines for the test. The loading rate of the expected strengths of the two sample sets was calculated using the formula below.

$$Loading\ Rate\ (kN/s) = \frac{loading\ rate\ (N/mm^2/s) \times Area\ of\ load\ applied\ surface\ (mm^2)}{1000} \quad (3)$$

Equation 3 - Formula for calculation of loading rate for each sample set

The loading rate was applied, and the bricks were compressed to failure. The load was then removed, and the hydraulic arm lifted. This allowed the sample to be removed and the loading area to be cleaned of any debris that splintered off during crushing. The process was then repeated for the remaining samples, and the compressive load at failure was recorded for each brick to the nearest 20 kN.

The results from the test were gathered, and the compressive strength of the bricks, f_b , is then multiplied by a shape factor, d, of 0.8. the shape factor was determined by the method of conditioning for the bricks. In this case both sample sets were oven dried. Details of the shape factor are given below, in Table 3. [*Appendix AC]*

Conditioning method	Shape factor, $\boldsymbol{d}$

Air drying condition	1.0
Oven dry condition	0.8
6% moisture content conditioning	1.2

Table 3 - Conditioning method and associated shape factor (BS EN 772-1)

The calculation using the shape factor was done to convert the compressive value into an equivalent compressive strength relating to its conditioning regime. This removed any bias surrounding the preparation and conditioning method.

A students t-test was performed on the compression values for both sets of the data to determine whether there is a significance between the new and reclaimed failure loads. The students t-test is a common analysis approach used to determine whether there is significance between two sets of data. The process compares the mean values of the reclaimed and new brick loads and calculates the probability (p-value) that the difference in the values occurred by chance. If p is below 0.05 (5%), it is considered statistically significant and that the difference is not random and reflects a real difference in means caused by differing brick strengths. In order to conduct the test a null and alternative hypothesis must be stated, in which one is accepted in relation to the result.

Null Hypothesis: The average compressive strength of the newly manufactured samples is equal to the average compressive strength of the reclaimed samples.

Alternative Hypothesis: The average compressive strength of the newly manufactured brick is not equal to the average compressive strength of the reclaimed samples.

The means and standard deviations of the results are used to determine the t-statistic, which is calculated using Equation 4 below.

$$t = \frac{(\mu_1 - \mu_2)}{\left(\sqrt{\left(\left(\frac{s_1^2}{n_1}\right) + \left(\frac{s_2^2}{n_2}\right)\right)}\right)} \tag{4}$$

Equation 4 - Calculation of t-statistic

If $p < 0.05$ then the null hypothesis can be rejected. Otherwise, the null hypothesis is accepted. The results of the test are included in 4.3.

The tests were conducted over two days as a result of the original compressive testing machine failing to crush the newly manufactured sample set. Therefore, the testing of the reclaimed bricks was conducted on the 15th of March 2023 in the heavy structure's laboratory at Edinburgh University – Kings Building. The testing of the newly manufactured bricks occurred the following week on a similar but stronger machine on the 22nd of March 2023 at the same location.

4 RESULTS

The following section analyses and compares the results of the three tests conducted: the determination of dimensions, water absorption and compressive strength respectively. This is done both illustratively using graphs and numerically using tables.

4.1 DETERMINATION OF DIMENSIONS & NET DRY DENSITY

It was observed during the dimension testing that the reclaimed samples are much rougher than the new bricks, with many cracks, fissures, and chips in the brick faces. The new bricks look much less damaged, which is to be expected. The analysis from the determination of dimensions and net dry density are provided in the table below, Table 4. [appendix AD-AE] contains the raw data and should be used for context. From the calculated dimensions, the dry bulk densities of each sample are displayed in the figure below, it displays the moving average densities of the samples and the individual deviation of density from the mean.

Brick type	**Average**			
	Bed area (cm^2)	**Volume (cm^3)**	**Dry Mass (g)**	**Dry bulk density (kg/m^3)**
Reclaimed	247.5 ± 9.7	1986.3 ± 162.1	3412.0 ± 335.70	1715.9 ± 91.34
New	218.9 ± 4.3	1605.5 ± 39.5	2772.3 ± 38.1	1800 ± 59.8

Table 4 - Table of brick dimensions and dry bulk densities

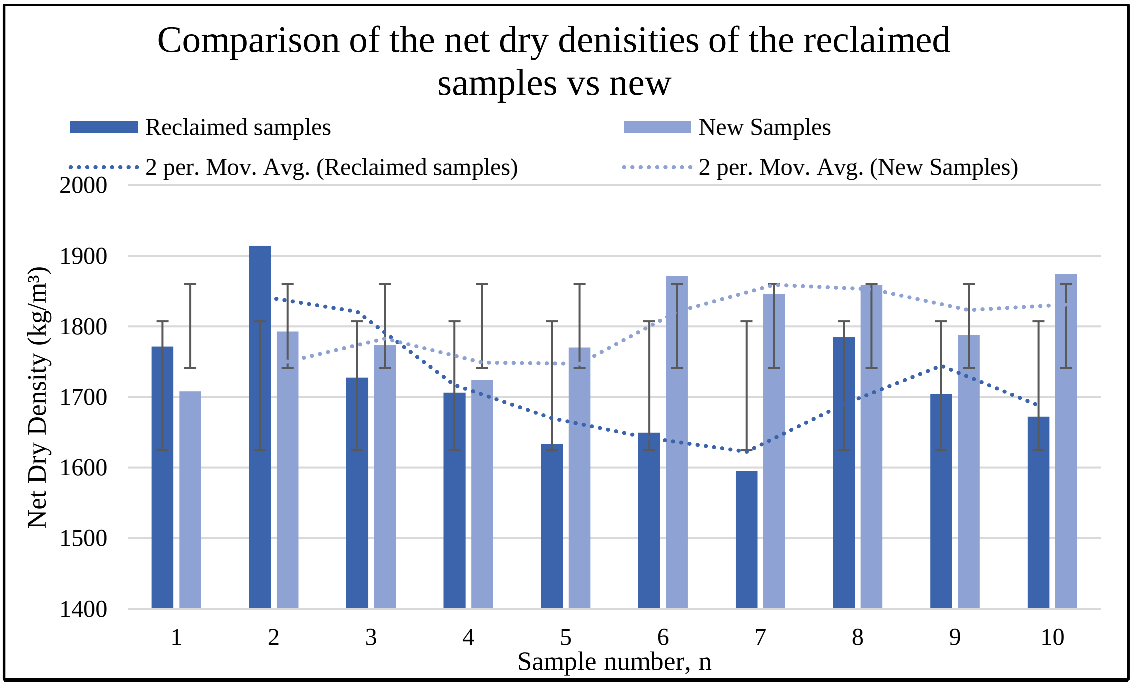

Figure 5 - Comparison of dry bulk densities of all samples

4.2 DETERMINATION OF WATER ABSORPTION

The results of each specimen from the determination of water absorption are displayed in the scatter graph below. It shows, on average, that the reclaimed sample set absorb a greater mass of water.

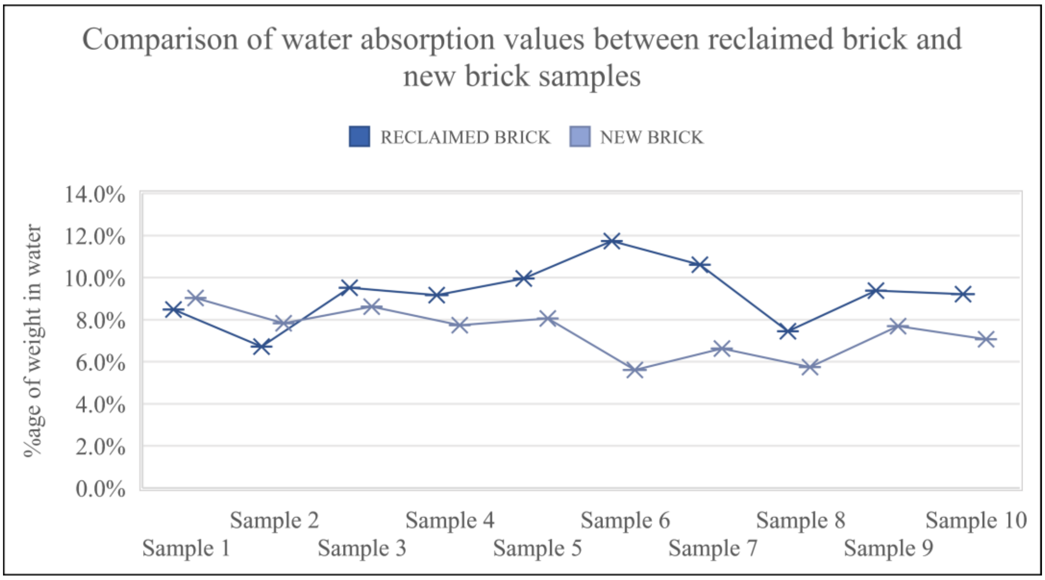

Figure 6 - Comparison of water absorption values of all samples

The mean, standard deviation and variance were also calculated to better understand the spread of results across each set. These values are given in Table 5 below and visualised as a box plot in Figure 7 below. *[Appendix AF-AG]*

Sample set	Mean	Standard deviation	Coefficient of variation
Reclaimed brick	9.23%	1.45%	0.02
New brick	7.40%	1.14%	0.01

Table 5 - Water absorption mean and deviation.

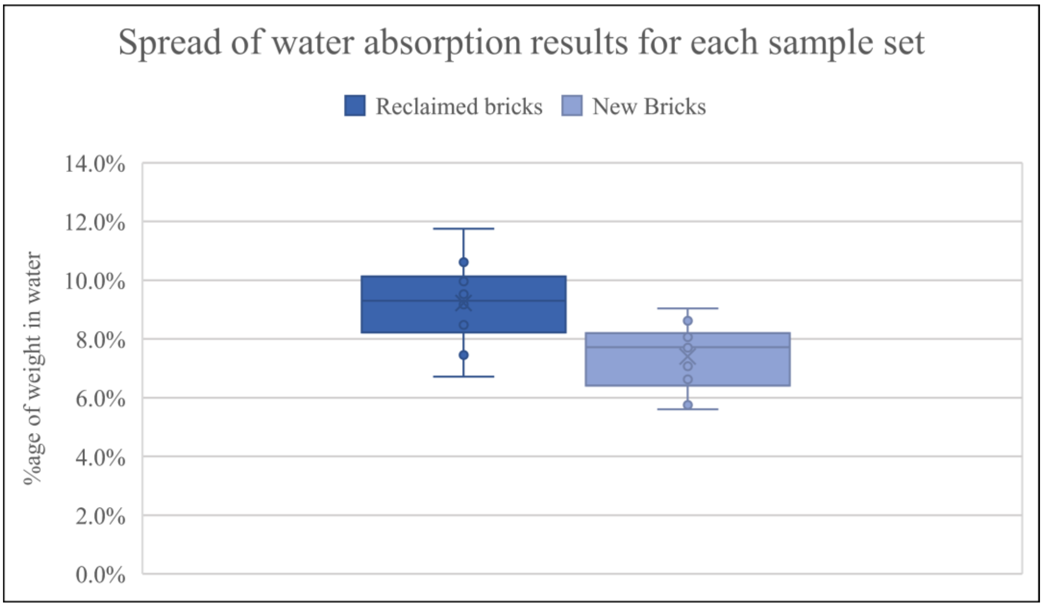

Figure 7 - Box plot showing spread of water absorption results.

4.3 Determination of compressive strength

The determination of compressive strength was the main test conducted in this study and therefore carries a much greater analysis of results. Figure 8 below gives a simple illustration of the load at failure for each of the samples. The graph shows the new bricks fail at a significantly greater load in comparison to the reclaimed samples. Exact values can be found in *Appendix AH.*

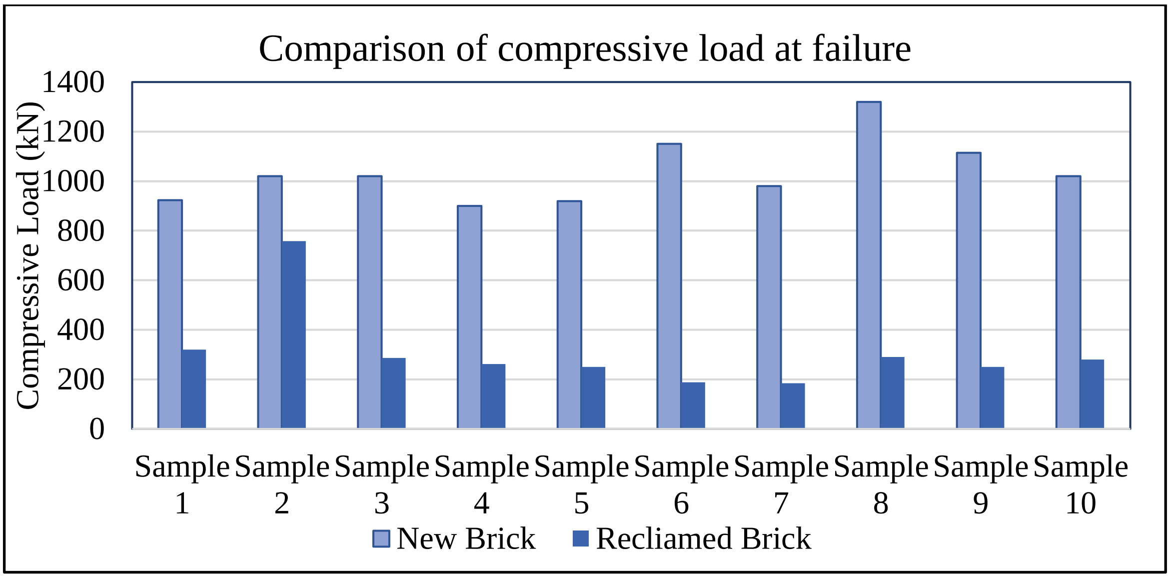

Figure 8 - Column chart displaying load at failure for both sample sets.

The spread of the failure loads is shown in Figure 9 below, it shows that while the new bricks performed better, there was a wide spread of results in each set and overall.

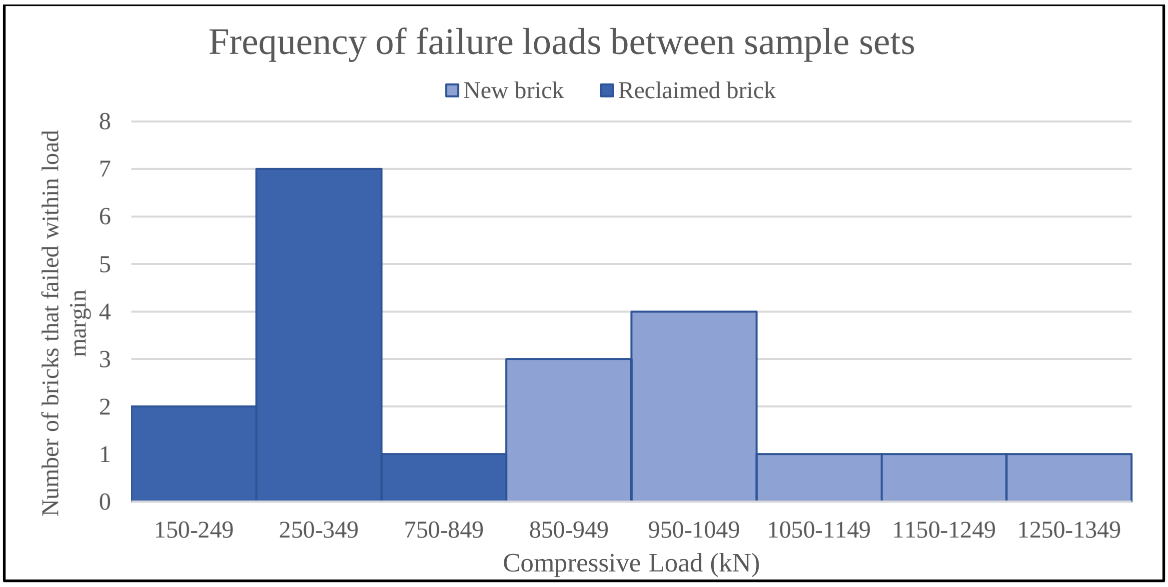

Figure 9 - Spread of compressive load at failure between sets.

By dividing the load at failure of each sample by its respective bed area, we can determine the compressive stress acting on each sample at the point of failure. This process can be seen in Table 6 and Table 7 below.

Reclaimed brick no.		1	2	3	4	5	6	7	8	9	10
Average	Length of brick (mm)	227.22	233.69	225.54	228.96	227.52	223.85	228.13	217.91	215.06	226.90
	Width of brick (mm)	111.67	106.547	107.01	111.257	107.407	111.457	114.143	107.78	107.237	113.233
	Height of brick (mm)	82.32	74.93	85.03	83.19	71.99	75.89	83.14	85.53	75.33	84.58
Area of brick (cm²)		253.74	248.98	241.35	254.73	244.37	249.49	260.39	234.87	230.63	256.93
Load at failure, P (kN)		320	758	286	262	250	188	184	290	250	280
Compressive Strength (N/mm²)		12.61	30.44	11.85	10.29	10.23	7.54	7.07	12.35	10.84	10.90
Average compressive strength										**12.41**	**N/mm²**

Table 6 - Determination of reclaimed samples compressive strength.

New brick no.		1	2	3	4	5	6	7	8	9	10
Average	Length of brick (mm)	215.61	209.59	214.84	213.51	214.43	210.27	211.86	213.12	215.66	214.84
	Width of brick (mm)	103.34	104.49	102.64	106.67	102.72	101.91	101.19	101.23	101.86	99.82
	Height of brick (mm)	72.07	72.06	75.48	73.25	74.07	73.56	73.92	72.55	73.77	72.75
Area of brick (cm²)		222.82	219.01	220.52	227.74	220.27	214.23	214.39	215.73	219.68	214.46
Load at failure, P (kN)		923	1020	1020	900	920	1150	980	1320	1115	1020
Compressive Strength (N/mm²)		41.42	46.57	46.25	39.52	41.77	53.67	45.71	61.19	50.76	47.56
Average compressive strength									**47.44**	**N/mm²**	

Table 7 - Determination of new samples compressive strength.

With the average compressive strength of both sets determined, it is necessary to include the spread of the calculated stresses to determine the frequency of the stresses to find patterns in the data.

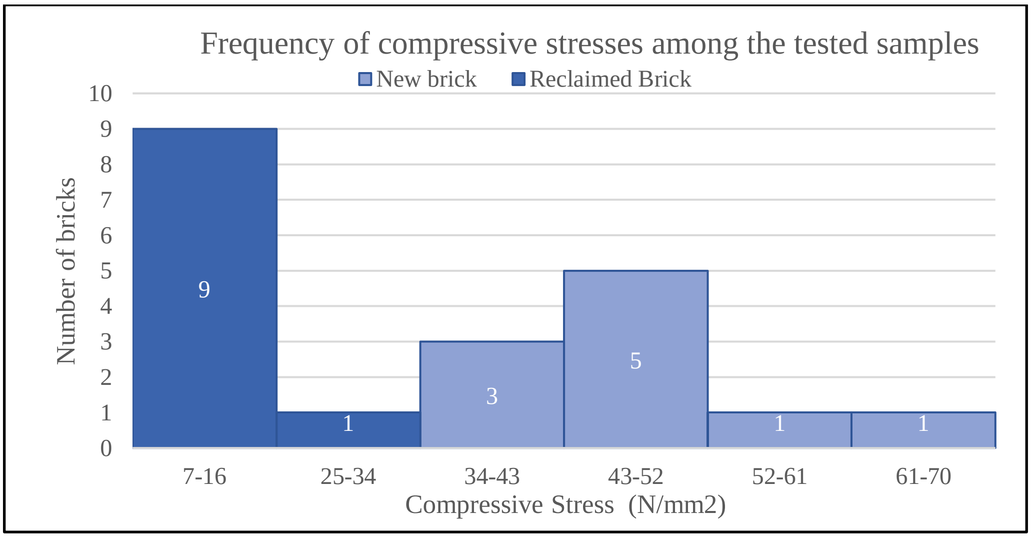

Figure 10 - Histogram showing spread of compressive stresses among the samples.

Photos from the failed samples are shown below in Figure 11. It reveals the fly ash content prevalent in the core of the reclaimed samples while the newly manufactured bricks have a blueish hue which is a discolouration created as a result of low oxygen during firing [58]. The left photograph shows the conical failure of the samples.

Figure 11 - Photos of bricks after crushing. New brick (L), Reclaimed brick (R)

As part of the analysis, the normalised compressive strength of the brick must be calculated to consider its conditioning process. the following table, Table 8, shows the calculation of the normalised stress.

Brick type	Compressive strength (N/mm²)	Shape factor, d	Normalised compressive strength, f_b (N/mm²)
Reclaimed	12.41	0.8	9.93
New	47.44		37.95

Table 8 - Calculation of normalised compressive strength

The student t-test revealed that the mean compressive strength of the new brick was significantly different from the mean compressive strength of the reclaimed sample set and therefore the null hypothesis was rejected. The p-value was calculated to be 0.0001 (extremely low) and therefore confirmed that there was a significance between the mean values between the sets.

5 DISCUSSION

5.1 SUMMARY

This study was conducted to compare the properties of compressive strength and water absorption of reclaimed and new bricks. The study found that there was a significant difference in compressive strength of the new and reclaimed samples, with the new bricks resisting a greater load overall, with an average strength of 47.44 N/mm^2 compared with 12.41 N/mm^2 reclaimed average. When calculating the normalised compressive strength, the values dropped to 37.95 N/mm^2 for newly manufactured samples and 9.93 N/mm^2 for the reclaimed. This was as a result of using the oven drying method to prepare the bricks. Through the analysis, there was a significant difference in properties between the two sample sets, with the old, reclaimed bricks showing signs of fatigue and structural wear, this was the expected result as stated in the hypothesis. The new bricks performed strongly in both tests, with high resistance to compressive stress and strong moisture repellent.

When it came to interpreting the consistency of the data, the reclaimed bricks had a greater deviation of results in all tests. Making them much less consistent in comparison to the more uniform results of the newly manufactured bricks.

5.2 INTERPRETATIONS OF RESEARCH

It is a reasonable and firmly supported hypothesis that that the higher failure load observed in the new bricks can be attributed to their increased density and lower porosity. It is widely accepted that a brick with high density tend to have an increased compressive strength due to the increased resistance to deformation under the applied stress. As the reclaimed bricks had a lower dry bulk density on average the particles had more room to deform and became more plastic in comparison. The new bricks, with their increased dry bulk density were more rigid and able to resist a greater stress. Many studies have demonstrated the same correlation between brick density and compressive strength including a study by Song and Yao which found the compressive strength of clay units increased with increasing density [59]

In the measurement of dimensions and calculation of dry bulk density, it was found that the reclaimed samples had a higher deviation of dimensions from the mean, showing that weathering and erosion over time had impacted the structure and material properties of the samples. This ultimately caused cracks and significant chips which were visible during inspection. To add, it was found that on average the newly manufactured sample had a greater dry bulk density compared to the reclaimed set, which could be associated with poorer firing standards in the manufacturing of the reclaimed bricks, compared to modern times. Further, the relationship between colour of the brick and its rate of absorption can also be accounted for by the manufacturing process. Specifically, the firing temperature during production affects the bricks porosity, resulting in a darker-coloured brick with larger pores at a high temperature.

This is because as the clay is fired, the water and other volatile compounds in the mixture evaporate leaving behind minerals that fuse together at high temperatures. This in turn increases the density of the brick and as a result of the gaps between particles closing, the porosity decreases. This process lowers the bricks capacity to absorb water. [60] [61]

It may also be said that the high content of fly ash coal in the reclaimed brick structure will have had a negative effect on its strength properties and its absorbed water content. The content of fly ash in the reclaimed samples was observed during the determination of compressive strength when the bricks reached failure and were ultimately broken. *Figure 11* shows the significant extent in which fly ash particles were mixed into the clay brick mixture. Fly ash and its use in bricks are known to present much poorer mechanical strength properties compared to that of normal clay bricks, as echoed by a paper written by Gadling and Varma [62]. The content of fly ash in the brick may also have impacted the water absorption properties of the reclaimed units, as fly ash on the exterior faces may have combusted during the firing process and created pores and cavities on the faces, which would have significantly reduced its resistance to weathering and allowed moisture to penetrate further into the brick as a result. This is a significant finding as fly ash clay bricks, according to existing literature, have a significantly higher water absorption content in comparison to standard red clay bricks [63]. Furthermore, due to the great age of the reclaimed bricks, the sample set will have been subjected to a harsh history of freeze-thaw weathering. This is a process in which moisture seeps into and accumulates in cracks and fissures on the brick faces and then freezes, causing the water to expand and the cracks to widen. The continuous cycle of this weathering action will have opened the small cracks caused from fly ash combustion during firing and increased the surface area of the brick faces significantly which allowed for a greater penetration of water during the determination of water absorption. These cracks may have also had a detrimental impact on the compressive strength of the bricks, as they had been weakened over time. Both consequences of freeze-thaw weathering are backed by existing literature into the freeze-thaw cycles and water absorption of masonry brick units. [64]

As a result of the much greater standard deviation of sample heights of the reclaimed sample set, it is presumed that the 6mm plywood sheets applied to the bed faces of the units failed to deliver a uniformly distributed load across the surface area of the bed. The unevenness of the brick translated through the plywood and resulted in extremely high, localised stresses on areas of the brick with the greatest height and much lower stresses on areas that lay at the lower end of the height deviation. This was visible on several of the samples where the corners failed by overwhelming shear force as opposed to crushing.

5.3 RESEARCH IMPLICATIONS

The results of the study confirm the lack of uptake in the implementation of reclaimed bricks into design and construction of buildings and structures. By choosing the easy and most risk adverse option of high-quality new bricks instead of reclaimed, designers and engineers can increase the structural integrity and longevity of the building. Ultimately eliminating the increased cost associated with reclaimed brick maintenance and replacements.

No assurance can be given that the samples of reclaimed brick accurately represent a delivery of consistent units. This test was performed on a very narrow batch of ancient bricks which are unlikely to represent all reclaimed bricks used in construction. Due to this, it is unlikely this individual batch of reclaimed bricks will affect the application of reusability of bricks in construction. The research also has implications for general sustainable construction practices. The study suggests that the implementation of reclaimed bricks back into structural environments may not always be the most appropriate option for promoting sustainability, as it may create a situation where sustainability is adopted over structural safety. Overall, the reuse of construction materials is a highly significant aspect of the construction industries sustainable goals, however the priority is strength and durability first.

5.4 LIMITATIONS OF RESEARCH

Firstly, it was not possible to obtain a perfect match when it came to procuring two sample sets exactly matching in all properties. Trying to obtain a new equivalent sample set was challenging as a result of advancements in material efficiency and modern manufacturing methods. The most popular brick in current supply across Britain is the class B modern engineered clay brick, which is designed for material efficiency, are denser, and have significantly larger strength characteristics [65]. Therefore, extra effort had to be taken to find brick samples that matched to as close as possible size, shape, and material.

Although the sample selection of ten was enough to meet the minimum threshold and provide reliable results, a larger-sample selection would have provided much greater validity and reliability of the results. However due to limitations procuring the reclaimed sample set, it was deemed unnecessary to expand the sample batch as the reclaimed bricks held a certain historical value to the Prestongrange museum which it was deemed inappropriate to exceed. Furthermore, as the reclaimed sample set contained bricks of varying shape and size, it was determined most suitable to use the specific bed area for each brick to determine the compressive load in N/mm^2. There was a range of around 22mm in the reclaimed sample length and 14mm for its width, which would have led to less accurate compressive strength figures as these dimensions make up the bed area needed to calculate the stress. Due to the consistency of the new brick set, having a standard deviation of 1.9mm for length and 2.1mm for width the compressive stress was determined from the average bed size of the entire sample set, as all the bricks were uniform and standardised.

It may have been possible that cracks, fissures, and holes developed during the cleaning process of the brick. Where mortar-brick bonds were strong a chisel and hammer may have damaged the bricks during initial preparation. This may have affected the water absorption of the bricks as the resistance to moisture will have been compromised partly or in full making it much easier for the moisture to penetrate the brick and increasing its moisture content. Further, the cracks may have weakened the structural integrity of the brick which would have affected its performance in the determination of compressive strength test.

There were numerous limitations associated with the compressive testing machine used during the determination of compressive strength of the masonry units. Firstly, the machine was an analogue machine dated to sometime between 1960-1970 and therefore was purely analogue and manually operated. This meant that only the load at failure could be recorded, and that the value was visually inspected from an analogue scale. The scale of the compressive force only provided loads in 20kN increments, which was understandably an inaccuracy. Therefore, the compressive loads on the scale had a tolerance of ±10 kN. An electronic compressive testing machine would have been preferred, both in order to achieve a more accurate reading for each brick and so that load/displacement curves could be obtained and analysed to calculate the modulus of elasticity, which would have been another predictor of the bricks physical properties that could be compared.

In the determination of net and gross dry densities of masonry units, it was deemed too difficult to accurately determine the gross dry density of the reclaimed units. The frog sizes across the sample set were unable to be precisely measured due to erosion of the frog edges and undefined shape of most samples. For the new bricks, the gross dry density will have been the same as the net dry density as there were no stamps, perforations, or imprinted frogs on any face of the units.

The influence of using two different compressive testing machines, one on the reclaimed samples and one on the new sample would have had a negligible effect on the results in comparison to the difference in strength between the two sets of brick. It should be said that the machines are calibrated to maintain consistency of results and therefore the results can be determined as valid. The testing machine for the new bricks was not able to achieve the calculated loading rate of 13kN/s or 780kN/min as a result of its age and hydraulic pumping pressure limitations. The machine applied compressive force using a gauge that ran from one to twenty with no units, and this scale did not translate to the load acting per second and was simply acting from lowest setting to highest.

5.5 RECOMMENDATIONS FOR FUTURE STUDY

In recent times, building practices and techniques have adopted for engineered bricks, in which material content in the brick is lower, while maintaining the usual brick properties of compressive strength and durability. For this case, the scope of the research may not accurately reflect the brick strengths that we see in modern construction project. Engineered bricks are often lighter as a result of cleverly designed holes in the brick. The new bricks sourced for this project were clay bricks to ensure the best possible match to the reclaimed bricks. Further research should consider the strength of bricks younger than 100 years and consider bricks that have been used in other applications such as walls, bridge piers and abutments, residential buildings, as well as previous industrial use which was the origin of the bricks used in this research. Further, bricks which have been made post metrification in the UK should be prioritised, as the reclaimed samples were designed in imperial units.

Greater variation of reclaimed brick dimensions means that the plywood would have done very little to distribute the load on each of the units. As the average deviation of dimensions for the reclaimed height was around 5mm. It means that the brick would have undergone high pressure at certain areas and much lower pressure elsewhere. In theory the plywood was used to reduce localised pressure on areas of the brick with extruding heights compared to the rest of the brick, however the successfulness of this cannot be fully determined, but evidence from the testing shows bricks with higher height deviations failed at a much lower load in comparison to those with smaller deviations. The placing of the plywood at the top and bottom faces was introduced in the standard to counteract this unevenness and ensure that the load being applied on the brick by the machine was distributed evenly. The plywood at the top would compress into the brick, and the brick would compress into the bottom piece of plywood. To increase the accuracy of the compression test, and allow for a more evenly distributed load, the plywood could be substituted for a capping layer of equally levelled gypsum. Future repetitions of this research should bear this in mind and as a recommendation.

For future repetitions of this test, electronic compressive testing machines should be encouraged as it was difficult to determine the accurate failure figure from the analogue gauge. With the help of an electronically controlled machine the compressive load at failure could be given and the stiffness of the bricks could be determined from load-displacement graphs provided by the computer. From this, the behaviour of the brick under compressive load could be analysed and stress-strain graphs could help determine the modulus of elasticity of the bricks.

Further testing of reclaimed brick samples should be undertaken to fully determine its suitability for reintroduction. For example, the determination of freeze-thaw resistance (BS EN772-22:2018) is another essential property for bricks as they are subjected to repetitive cycles of freeze-thaw weathering due to the UK’s mild climate. Cold and warm weather in the UK means that it is vital for bricks used in weather exposed environments to be able to resist weathering processes to safe levels.

6 CONCLUSION

Purely from the results of the investigation, it can be determined that new bricks perform significantly better both in terms of compressive strength and water absorption compared to reclaimed units. Due to the higher and more uniform compressive strength of the new units, they are more suitable for construction projects that require strength and longevity. There is significantly less water absorption in the new bricks which makes them a much more advantageous option for applications involving water, such as sewerage systems or building exteriors as they are more resistant to water penetration and damage.

The associated cost burden of reclaimed bricks is more a reflection of the cost of reclamation as opposed to the intrinsic quality of the material, as this study shows. As a result of efficient modern manufacturing, modern new bricks are generally less expensive than reclaimed bricks and their quality and physical property are more consistent and much more easily designed for. By minimizing the strength uncertainty, which is by far the biggest barrier in their implementation, there is great potential for the reuse of bricks in structural settings. Furthermore, by tackling the intensive labor requirements and knock on effects on reclamation cost, the price of reclaimed bricks can fall and, in the eyes of the industry, can become a much more realistic and feasible option to consider during both design and procurement of materials.

When it comes to masonry design using reclaimed samples, there are two important factors which are attributed to the brick properties according to Eurocode 6: Masonry design. These factors are the characteristic compressive strength of masonry (f_k) and the partial safety factor for material strength (γ_m). The value of γ_m is dependent on the degree of quality control practiced by manufacturers and the standard of site supervision, testing and workmanship achieved during construction [66]. In the UK, these values are found in NA.1 in the standard. Currently the highest and safest value is 2.7 and this applies to unreinforced masonry in direct or flexural compression and which >5% of the units will not meet their declared compressive strength. The evidence presented in this report suggests that the percentage of units not able to meet the strength classification of 11-20 N/mm^2 was 50%. Therefore, it can be said with confidence that the factor of safety for the reclaimed brick material must be much greater than 2.7 due to uncertainty and inconsistency of strength properties. And as calculated the characteristic compressive strength of the reclaimed units was found to be approximately 12 N/mm^2, which would be used to calculate the design compressive strength of the masonry and the masonry structures suitability against its loading according to Eurocode 6 [66]. Therefore the biggest challenge in the design using reclaimed bricks is determining this factor of safety. And as the deviation of units meeting the declared strength is likely to vary massively, defining this will be extremely problematic and may be impossible without non-destructive compressive tests for bricks.

And as the UK Government aims to tackle the disposal of construction waste through taxation of landfill usage, the issue will not be addressed. The push for the reuse of materials is industry led through research which leaves the door open for environmentally friendly practices that cannot be resolved without innovative and fresh legislation set out by the Government.

To conclude all points, this study ultimately supports the use of new bricks over reclaimed bricks for projects requiring high compressive strengths and low water absorption. Due to the limiting physical properties of the reclaimed units discovered in this paper balanced with the importance of sustainability, it should be said that their reusability should be encouraged but caution should be taken. Users of reclaimed bricks must be conscious of the diminished strength and quality of the brick. Their compressive resistance is often more sporadic and with a much larger deviation from the mean, therefore a thorough examination and evaluation of the bricks fitness for purpose should be conducted. However, due to the lack of non-destructive property testing methods for masonry bricks, determining their strength is extremely difficult. With an optimistic agenda push from governments and industry, and by finding a quick, reliable testing solution for reclaimed bricks, the potential for the reuse of brick into structural settings can fully be explored.

However, by coming to this conclusion it is important, now more than ever, that the specific requirements of each project is taken into consideration when procuring construction materials and that a balance is struck between the need for strength and durability with the ambition and wanting a structure with the best sustainable practice and an aesthetic look. Overdesign is not only a waste of money but is a waste of resource, for single or two-storey domestic buildings at most, it is unlikely that the strength requirements would limit the use of these reclaimed brick.

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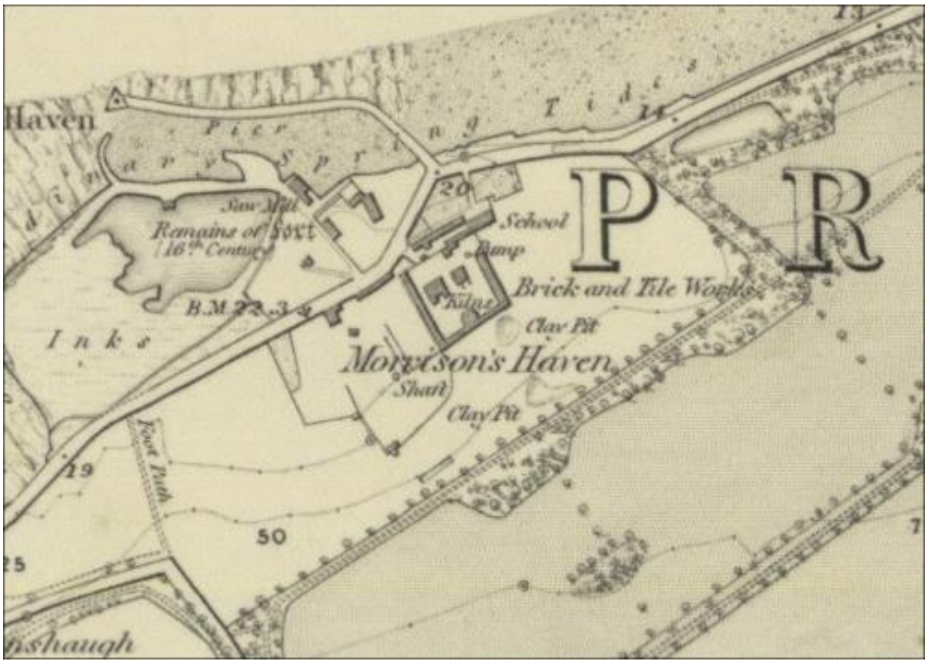
8 APPENDIX



Appendix A – Prestongrange Site map (circa 1907) [51]

Appendix B – Prestongrange Site map (circa 1855) [51]

Appendix C – Photo taken of Hoffman Kiln Chimney Stack

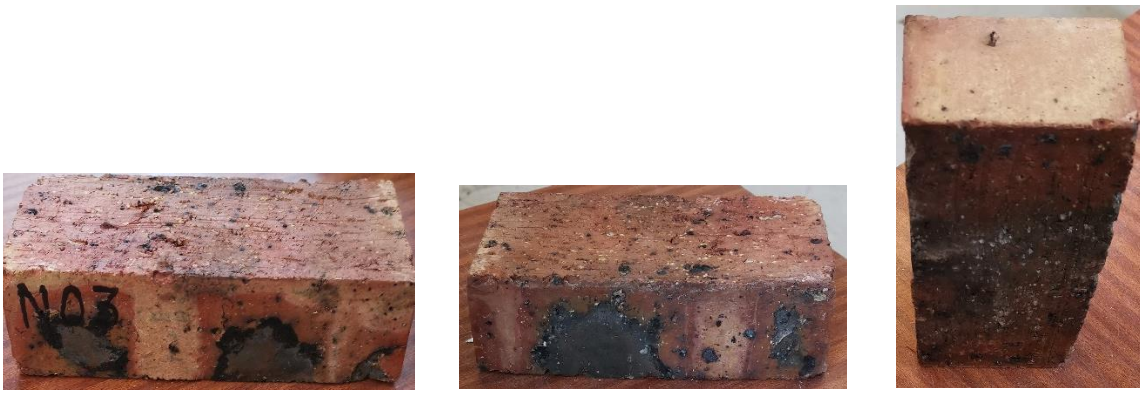
Appendix D – Photo of the inside of the Hoffman Continuous kiln [51]

Appendix E – Centre of Kiln [51]

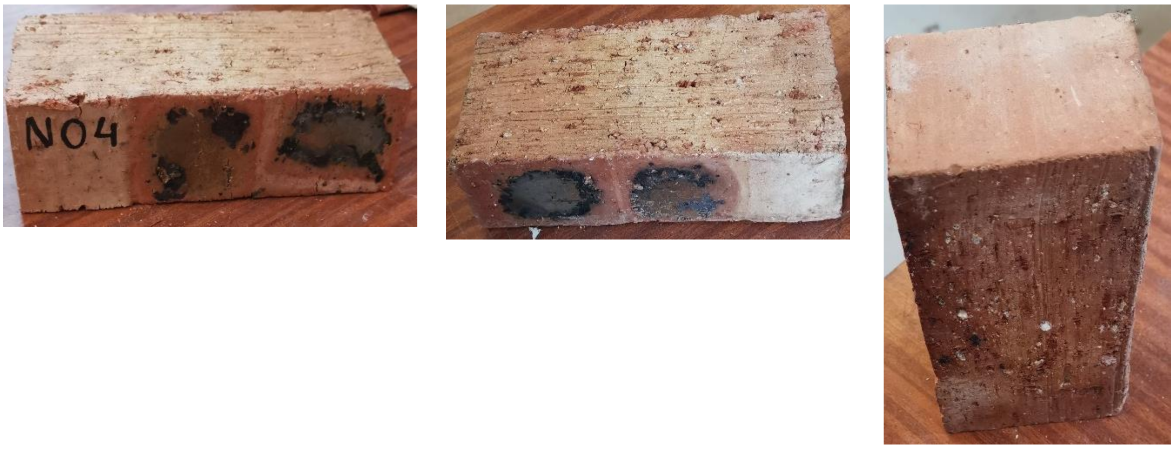
Appendix F – Source of the reclaimed bricks from Prestongrange Museum

Appendix G – New brick 1 photos

Appendix H – New brick 2 photos



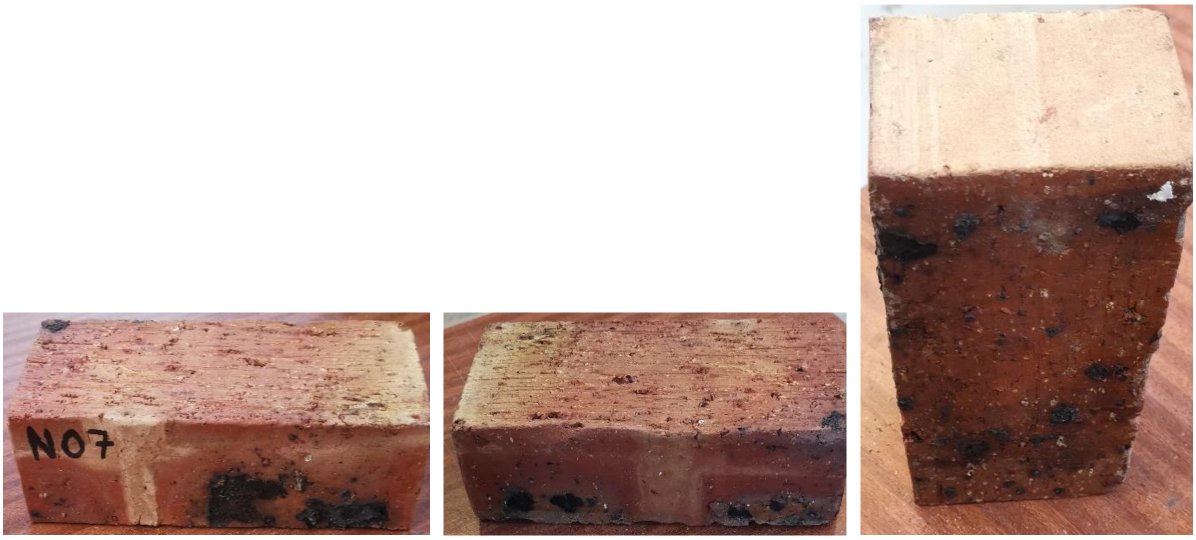
Appendix I – Reclaimed brick 3 photos



Appendix J – Reclaimed brick 4 photos

Appendix K – Reclaimed brick 5 photos

Appendix L – Reclaimed brick 6 photos



Appendix M – Reclaimed brick 7 photos

Appendix N – Reclaimed brick 8 photos

Appendix O – Reclaimed brick 9 photos

Appendix P – Reclaimed brick 10 photos

Appendix Q – Used brick 1 photos

Appendix R – Used brick 2 photos

Appendix S – Used brick 3 photos

Appendix T – Used brick 4 photos

Appendix U – Used brick 5 photos

Appendix V – Used brick 7 photos.

Appendix W – Used brick 9 photos

Appendix X – Used brick 10 photos

Appendix Y - AJ-6200E precision balance machine used to weight the samples

Table B.1 — Surface preparation and conditioning of units

Masonry unit type	Product specifications	Surface preparation	Conditioning masonry
Clay	EN 771-1	7.2.4	7.3.2
Calcium silicate	EN 771-2	7.2.4	7.3.3 a)
Aggregate concrete	EN 771-3	Units h < 100 mm 7.2.4 Units h ≥ 100 mm 7.2.4 or 7.2.5	7.3.2 a) or 7.3.5
Autoclaved aerated concrete	EN 771-4	7.2.4	A1 7.3.3 b) or 7.3.4 A1
Manufactured stone	EN 771-5	7.2.4 or 7.2.5	7.3.2 a) or 7.3.5
Natural stone	EN 771-6	7.2.4	7.3.2 a)

Appendix Z – Surface preparation according the EN 772-1 [47]

Expected Compressive Strength (N/mm^2)	Loading Rate (N/mm^2)/s
<10	0.05
11 – 20	0.15
21 – 40	0.3
41 – 80	0.6
>80	1.0

Appendix AA – Table of Loading Rates

Newly Manufactured brick		Reclaimed Brick	
Loading rate (N/mm2)/s	Loading rate (N/s)	Loading rate (N/mm2/s)	Loading rate (N/s)
0.6	13401.0	0.15	3826.7
	12882.3		3921.9
	12811.3		3680.7
	13390.4		3797.6
	12846.0		3582.2
	12366.7		3650.6
	12547.9		3798.3
	12737.6		3619.0
	12844.4		3363.3
	12481.6		3715.1
0.6	12830.9	0.15	3695.5

Appendix AB – Calculated Loading rates of each sample and the average

for units conditioned in accordance with 7.3.2 or 7.3.4	1.0
for units conditioned in accordance with 7.3.3	0.8
for units conditioned in accordance with 7.3.5	1.2

Appendix AC – Shape factors associated with conditioning method. [47]

BRICK ID	LENGTH (l)						WIDTH (w)						HEIGHT (h)					
	l1	l2	l3	av.	var	s.dev	w1	w2	w3	av.	var	s.dev	h1	h2	h3	av.	var	s.dev
U01	228.43	227.91	225.32	227.22	2.7751	1.6659	111.68	109.2	114.13	111.67	6.0763	2.465	83.16	77.46	86.34	82.32	20.243	4.4992
U02	233.51	233	234.55	233.69	0.624	0.79	111.97	105.55	102.12	106.55	25.001	5.0001	72.11	76.21	76.47	74.93	5.9812	2.4456
U03	225.74	226.84	224.03	225.54	2.005	1.416	108.70	105.9	106.43	107.01	2.2123	1.4874	82.28	90.9	81.92	85.033	25.846	5.0839
U04	228.29	230.3	228.29	228.96	1.3467	1.1605	110.90	109.22	113.65	111.26	5.0016	2.2364	79.43	87.44	82.71	83.193	16.215	4.0268
U05	228.66	227.67	226.22	227.52	1.506	1.2272	104.44	108.05	109.73	107.41	7.3064	2.703	74.80	75.51	65.68	71.997	30.051	5.4819
U06	223.63	222.6	225.31	223.85	1.8712	1.3679	108.83	111.56	113.98	111.46	6.6386	2.5766	75.76	70.25	81.67	75.893	32.617	5.7112
U07	228.17	227.1	229.12	228.13	1.0213	1.0106	110.98	115.33	116.12	114.14	7.661	2.7679	85.10	75.43	88.9	83.143	48.232	6.9449
U08	217.75	216.94	219.05	217.91	1.133	1.0644	110.80	107.44	105.1	107.78	8.2092	2.8652	84.54	90.95	81.11	85.533	24.946	4.9946
U09	216.43	213.1	215.66	215.06	3.0392	1.7433	103.60	108.45	109.66	107.24	10.285	3.207	70.11	76.31	79.58	75.333	23.136	4.81
U10	226.93	225.87	227.9	226.9	1.0309	1.0153	109.14	114.66	115.9	113.23	12.951	3.5987	83.71	80.22	89.8	84.577	23.507	4.8484
N01	215.07	214.55	217.22	215.61	2.0036	1.4155	103.85	101.24	104.94	103.34	3.615	1.9013	72.35	70.33	73.55	72.077	2.6481	1.6273
N02	210.35	207.55	210.88	209.59	3.2016	1.7893	102.07	105.09	106.32	104.49	4.7826	2.1869	72.58	70.55	73.05	72.06	1.7653	1.3286
N03	213.8	214.8	215.93	214.84	1.1356	1.0657	99.87	104.33	103.73	102.64	5.8585	2.4204	73.35	75.88	77.2	75.477	3.8276	1.9564
N04	214.92	213.44	212.16	213.51	1.9077	1.3812	103.84	107.61	108.55	106.67	6.2134	2.4927	70.46	74.05	75.23	73.247	6.1722	2.4844
N05	212.76	214.25	216.29	214.43	3.1404	1.7721	100.63	104.32	103.22	102.72	3.589	1.8945	71.31	75.51	75.39	74.07	5.7168	2.391
N06	207.44	209.61	213.76	210.27	10.312	3.2113	99.36	103.9	102.46	101.91	5.3825	2.32	71.56	75.33	73.8	73.563	3.5952	1.8961
N07	212.77	210.1	212.72	211.86	2.3326	1.5273	98.29	102.88	102.4	101.19	6.3651	2.5229	71.73	74.79	75.23	73.917	3.6345	1.9064
N08	212.89	210.12	216.34	213.12	9.7106	3.1162	99.72	101.41	102.55	101.23	2.0274	1.4239	71.40	73.66	72.58	72.547	1.2777	1.1304
N09	213.71	215.43	217.85	215.66	4.3257	2.0798	100.17	102.89	102.53	101.86	2.1829	1.4775	72.34	74.55	74.42	73.77	1.5379	1.2401
N10	212.88	216.22	215.41	214.84	3.0354	1.7422	97.72	100.19	101.56	99.823	3.7872	1.9461	70.49	73.7	74.05	72.747	3.85	1.9622

Appendix AD – Calculation of absolute, average and deviation of dimensions

BRICK ID	Bed Area (mm2)		Volume (mm3)		Mass (g)	Dry Bulk Densities (Kg/m3)	
	Result	st. dev	Result	st. dev		Result	st. dev
U01	253.7366	9.7	2088.8	162.1	3757.8	1799.0583	109.9
U02	248.9854		1865.6		3601.1	1930.2309	
U03	241.3468		2052.3		3614.8	1761.3674	
U04	254.7333		2119.2		3604.2	1700.7038	
U05	244.3681		1759.4		2918.6	1658.8678	
U06	249.492		1893.5		3041.8	1606.4457	
U07	260.3952		2165.0		3437.6	1587.7877	
U08	234.867		2008.9		3683.2	1833.4651	
U09	230.6267		1737.4		2869.9	1651.8185	
U10	256.9264		2173.0		3591.4	1652.7212	
N01	222.822	4.3	1606.0	39.5	2759.9	1718.4832	45.4
N02	219.0111		1578.2		2793.7	1770.1756	
N03	220.5224		1664.4		2777.3	1668.6441	
N04	227.7404		1668.1		2787.8	1671.2079	
N05	220.2731		1631.6		2740.8	1679.8313	
N06	214.2791		1576.3		2760.1	1750.9576	
N07	214.3845		1584.7		2770.0	1747.9851	
N08	215.7309		1565.1		2817.2	1800.0764	
N09	219.6819		1620.6		2768.4	1708.2758	
N10	214.4571		1560.1		2747.6	1761.1581	

Appendix AE – Calculation of net dry density of all samples

Brick ID	Orig. mass	Dry mass	Wet mass	moisture content
U01	-	3757.8	4105.91	8.48%
U02	-	3601.13	3860.32	6.71%
U03	-	3614.77	3995.36	9.53%
U04	-	3604.15	3967.95	9.17%
U05	-	2918.56	3241.45	9.96%
U06	-	3041.77	3446.64	11.75%
U07	-	3437.58	3845.87	10.62%
U08	-	3683.24	3979.86	7.45%
U09	-	2869.85	3167.23	9.39%
U10	-	3591.36	3955.86	9.21%
Av.	-	3412.02	3756.65	9.23%

Appendix AF – Moisture content of used sample set

Brick ID	Orig. mass	Dry mass	Wet mass	moisture content
N01	-	2759.93	3034.2	9.04%
N02	-	2793.68	3030.98	7.83%
N03	-	2777.34	3039.3	8.62%
N04	-	2787.78	3021.57	7.74%
N05	-	2740.75	2980.97	8.06%
N06	-	2760.05	2924.08	5.61%
N07	-	2769.96	2966.51	6.63%
N08	-	2817.22	2989.08	5.75%
N09	-	2768.42	2999.31	7.70%
N10	-	2747.59	2956.68	7.07%
Av.	-	2772.27	2994.27	7.40%

Appendix AG – Moisture content of used sample set

Brick type	Sample number										Mean	St dev
	1	2	3	4	5	6	7	8	9	10		
Reclaimed Brick	320	758	286	262	250	188	184	290	250	280	306.80	164.26
New Brick	923	1020	1020	900	920	1150	980	1320	1115	1020	1036.80	128.46

Appendix AH – Raw compressive loads at failure for all samples

NEW			RECLAIMED		
UNIT	LOAD	time to failure (s)	UNIT	LOAD	time to failure (s)
N01	923	71.9	U01	320	86.6
N02	1020	79.5	U02	758	205.1
N03	1020	79.5	U03	286	77.4
N04	900	70.1	U04	262	70.9
N05	920	71.7	U05	250	67.6
N06	1150	89.6	U06	188	50.9
N07	980	76.4	U07	184	49.8
N08	1320	102.9	U08	290	78.5
N09	1115	86.9	U09	250	67.6
N10	1020	79.5	U10	280	75.8

Appendix AI – Time taken for each sample to reach failure.

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