Use of crushed brick in reinforced-earth railway structures

■ **Simon Ellis** BSc (Hons), MICE, CEng

Senior Project Manager, Transportation Division, Mott MacDonald, Croydon, UK (current); Formerly Senior Project Engineer, Network Rail Thameslink KO2 Team (seconded from Mott MacDonald), London, UK (BDU Project)

■ **Andrew Goodwin** BSc (Hons), PGCE, PhD, MICE, CEng

Director, Surepath Training, Chesterfield, UK (current); Formerly Divisional Director, Buildings and Infrastructure Division, Mott MacDonald, Sheffield, UK (BDU Project)

■ **Elizabeth Laycock** BEng, MEd, PhD, MIMS, FGS

Lecturer, Department of the Natural & Built Environment, Sheffield Hallam University, Sheffield, UK

■ **Chris Hurst** BSc (Hons), PhD, FGS

Principal Engineer, Buildings and Infrastructure Division, Mott MacDonald, Sheffield, UK

The Bermondsey Dive-Under (BDU) scheme is a fundamental part of UK's Thameslink Programme. The scheme involves extensive demolition of 900 m of masonry viaduct followed by the construction of 900 m of new structures, 200 m of reinforced-earth structures and 200 m of embankment modifications. Crushed brick is typically not used as a structural fill material in the UK due to concerns over its friability and associated long-term performance. This paper describes a study undertaken in 2012 that examined the viability of recycling the demolished brickwork material into a crushed engineered fill material for use in the BDU permanent works. The overarching objective of the study was to seek to reduce the scheme's significant volumes of both imported fill and exported demolition material, with associated sustainability advantages in addition to the environmental and safety benefits resulting from the significantly reduced lorry movements from London's streets. The paper details the sampling and testing of brickwork that was undertaken and presents the findings from the study. The paper also discusses some of the issues associated with introducing innovation within major work programmes. The BDU scheme is currently under construction and is scheduled for completion in 2017.

1. Introduction

The Bermondsey dive-under (BDU) scheme (Figure 1) is a railway project located in the Bermondsey area of southeast London and forms a key part of the £6.5 billion Thameslink Programme. This ongoing programme in southeast England involves upgrading and expanding the existing Thameslink rail network. The purpose of the BDU grade separation scheme is to remove an existing bottleneck that severely limits the number of trains that can pass through London Bridge Station. This scheme involves rerouting four elevated existing lines down through a new box structure that will support the two Thameslink (fast) lines above.

To achieve the necessary vertical separation, the scheme involves partial to full demolition of four sections of masonry viaduct totalling ~900 m, six bridges and a number of retaining structures, all within the constraints of a constrained urban setting (Figure 2). The new structures consist of four sections of concrete viaduct (totalling ~550 m), five bridges, a 135 m long concrete box structure, 200 m of reinforced-earth structures and ~100 m of retaining walls. Earthworks include new sections of embankment and raising or reprofiling existing embankments.

As part of the preliminary design (Stage 4 of Network Rail's *Governance for Railway Investment Projects* (GRIP)

Figure 1. Artistic impression of BDU scheme (Tony Gee & Partners)

Figure 2. Eastern end of BDU site

framework), the designer (Tony Gee and partners) proposed that bricks from the demolished viaducts should be reused or recycled in the permanent works where possible. As the likely performance of the crushed brickwork was not known, Network Rail (NR) commissioned Mott MacDonald to investigate the viability of using crushed brick as an engineered fill material within the BDU scheme. In partnership with Sheffield Hallam University, the research study included a literature review, brickwork sampling and material characterisation testing, and the engineering interpretation of the results.

This paper summarises the background to, and extent of, the research trial. It then provides a brief overview of how the use of crushed bricks has been implemented in practice during the detailed design phase and construction works to date, before discussing the overall findings and presenting engineering recommendations for future practice.

2. Background

2.1 Sustainability requirements

In addition to pushing for higher levels of safety, reliability and transparency, NR places sustainable development at the heart of its culture (NR, 2013). In practical terms for this project, the Thameslink Programme Sustainable Development Policy required delivery of sustainable solutions that represented value for money within the available budget and increased resilience to future changes in climate. It required also that resource efficiency be maximised in planning, design and construction, including adoption of the waste hierarchy to minimise waste during design and construction. Implementation of this policy leads to scheme-wide initiatives such as reducing congestion and delays in the overall transport system and introducing longer and more energy-efficient rolling stock.

The sustainability driver was further embedded into the detailed design and construction planning for the BDU through the design drivers set out by NR and captured through the GRIP4 Stage Site Waste Management Plan. On the basis of the BRE SMARTWaste template (<http://www.smartwaste.co.uk>), the plan identified at its highest level the reuse of the existing viaducts as far as possible to avoid waste generation, and included a requirement to recover 90% of demolition and excavation waste by weight, with a stretch target of 95%. Potential sources of waste included ballast, timber sleepers, steel from existing girder bridges and masonry. It was estimated that up to 12 500 m³ of potential masonry waste would be generated, equivalent to ~1000 waste disposal-related lorry journeys.

2.2 Design requirements

NR requirements for reinforced-earth embankments and structures are included in Standards NR/L3/CIV/071 (NR, 2011) and NR/L3/CIV/140/52 (NR, 2010). Key requirements relevant to the specific use of crushed brick are as follows.

- The design, materials specification and construction methods adopted for earthworks for reinforced soil and anchored earth structures shall be in accordance with BD 70/03 (HA, 2003).
- Reinforced soil and anchored earth structures shall be designed to BS EN 8006-1 (BSI, 2010a) and HA 68/94 (HA, 1994).
- Acceptable material for use as general granular fill shall comply with the requirements for classes 1 and 3 of Table 6/1 of the Specification for Highway Works (SHW) (HA, 2005).
- Fill to reinforced soil shall be classes 6I, 6J, 7C or 7D in Table 6/1 of the SHW, with an effective angle of shearing resistance (ϕ') of at least 36° and a grading uniformity coefficient of at least 2.

The specified design code BS EN 8006-1:2010 (BSI, 2010a) as amended by BD 70/03 contains recommendations and guidance for the design, construction and maintenance of reinforced soil (or fill) structures, slopes and foundations. Key recommendations pertinent to the use of crushed brickwork are as follows.

- Fill material for reinforced-earth structures should be selected frictional fill (class 6I/6J for granular frictional fill), although non-standard fills may be used with increased frequency of testing.
- Where metallic soil reinforcement (or other metallic elements) is to be installed, fills shall meet the electrochemical limitations given in BS EN 14475:2006 (BSI, 2006).
- Friable fill material (i.e. material which is susceptible to degradation by water and pressure over time) should not be used in reinforced soil structures.
- Construction trials should be undertaken where there is no previous experience of use of the proposed fill material with the type of soil reinforcement being considered.

BS EN 14475:2006 (BSI, 2006) details the general principles for the construction of reinforced-earth structures, slopes and embankments. The standard highlights that fill should be selected to meet the specific properties required by the design and project specification. Factors to be considered when selecting a reinforced fill material are laid out and include aspects such as long-term behaviour, maximum particle size, drainage properties, aggressivity, fill strength and reinforcement interaction, and frost susceptibility. Furthermore, the standard states that degradable fill materials should not be used unless specific validation studies are carried out, and material not susceptible to frost shall be used on surfaces exposed to sub-zero temperatures.

2.3 BDU permitted engineered fill materials

The BDU reinforced-earth structure scheme that was proposed at preliminary design stage (GRIP stage 4) composed of three separate reinforced-earth structures. The design consisted of reinforced earth walls of modular blockwork facing units with polymeric geogrid reinforcement. Fill material was specified as a type 6I/6J free draining granular material with a minimum ϕ' of 36°. Side and top fill material was specified as 'non-friable and frost-resistant material' with the core specified as a type 6I/6J material including recycled aggregate. The design for a typical reinforced-earth structure is shown in Figure 3.

Aside from the reinforced-earth structures, the preliminary design specified the use of the following other fill materials.

- Class 1A general fill for new and modified railway embankments and BDU box.

Figure 3. Preliminary design detail for typical reinforced-earth structure (based on drawing by Tony Gee & Partners)

- Class 6N free draining fill behind retaining walls.
- Lightweight fill (maximum unit weight of 5 kN/m^3) for raised railway embankments.

The use of crushed brick as, or as part of, the class 1A and 6I/6J materials was permitted subject to validation by testing.

3. Experimental investigation

3.1 Scope of study

The purpose of the study was to investigate the potential for reusing the crushed brickwork within the BDU permanent works, as proposed by the preliminary design team. The output from the study was to be a report that would provide NR with independent guidance on the potential suitability and limitations on the use of crushed brick, and provide the detailed design and construction teams with initial site-specific test data from which they could develop their design and construction proposals. It was acknowledged that further testing by the design and construction teams would be required to provide full validation, along with crushing trials to determine the optimum material grading.

Due to programme constraints and the limited amount of sample material that was available to the study from earlier site investigations, a full research quality test programme was not feasible. It was therefore necessary to prioritise the testing and adopt a pragmatic strategy for processing and testing the brick

samples to make the most use of what was available. The focus of the study was the high-volume, more structurally demanding class 6I/6J material for the reinforced-earth structures.

3.2 Test programme considerations

Consideration of the in-service requirements of the fill indicated the following.

- The crushed bricks in the reinforced-earth structure are likely to be well drained, indicating that testing in drained rather than saturated conditions would be most relevant.
- Compressibility and strength were recognised as potential issues, for example, within the influence zone of dynamic track loads and where hard facings are specified. With the shortfall in available material (as discussed previously), and existing research indicating the likelihood that compressibility would be significantly affected by the future on-site grading, it was agreed that compressibility and permeability tests would not be undertaken as part of the study, but would be considered at the detailed design stage.
- The proposed use of the fill in an elevated position could promote frost penetration to significant depth, indicating that one focus of the testing should be durability under freeze–thaw conditions.
- Classification, compaction and shear strength data would be required for the specification of crushed bricks, which indicated that some such tests should be included.

The experimental programme devised, thus comprised two main elements.

- Classification, compaction and strength testing using standard methodologies.
- Freeze–thaw testing over moderate and longer term freeze–thaw temperature cycles.

3.3 Sampling and test specimen preparation

The material used for the brick research study was obtained from cores extracted during earlier structural investigations in 2011 along with limited additional cores specifically taken for the study in 2012. The cores were delivered to Sheffield Hallam University and weighed, logged and photographed. Examination of the cores and review of the historical development of the viaducts allowed the brick stocks to be characterised into two disparate types: ‘red’ stock bricks found in the viaduct structures dating from the 1840s which had high mortar content and were irregular in shape; and ‘yellow’ stocks from the late 1800s viaducts which had a low mortar content and were noted to be broadly consistent in size and shape. Approximately 60 kg of core sample for each type of stock was provided.

Following description of the cores, trials were undertaken to establish a core crushing protocol that would generate a suitably graded recycled aggregate. A jaw crusher was selected to crush the bricks with a minimum aperture of 45 mm initially selected to minimise losses due to generation of fines. After the primary crushing cycle, grading tests on the aggregate produced were carried out according to BS EN 933-1:2012 (BSI, 2012). Secondary crushing was deemed necessary to increase conformity with 6I/6J grading; this was restricted to particles

retained on the 63 mm sieve to minimise the documented effect of apparent aggregate durability increase with repeated crushing. The grading produced was still not fully compliant with the 6I/6J requirements and the red and yellow brick samples had significantly different gradings to each other. The yellow stock material retained on the 63 mm sieve was crushed for a third time to bring both materials to a comparable grading. Although it would have been preferable to have a fully 6I/6J compliant grading, further crushing would have resulted in inadequate material available for frost testing.

3.4 Standard testing

Both red and yellow brick samples were subject to classification testing as detailed in Table 1.

3.5 Freeze–thaw testing

Freeze–thaw testing was undertaken in a specialist chamber at Sheffield Hallam University (Figure 4) and broadly followed the standard test method given in BS EN 771-1:2011 (BSI, 2011).

The majority of the test samples were tested in air, a departure from the standard test method, but deemed to better replicate the likely conditions in service (Laycock, 2002). A limited number of freezing tests under the saturated conditions specified in BS EN 1367-1:2007 (BSI, 2007) were also undertaken for comparison purposes.

The samples were placed in stainless steel test containers of 2000 ml nominal capacity above a stainless steel mesh liner so that they were free draining. A sump was provided below the

Fill property	Test parameter	Test standard
General	Bulk density	BS EN 1377-2:1990 (BSI, 1990a)
	Moisture content	
Particle characteristics	Mineralogy (XRD)	BS EN 13925-1:2003 (BSI, 2003)
	Particle size distribution	BS EN 933-1:2012 (BSI, 2012)
	Particle density	BS EN 1097-6:2013 (BSI, 2013)
Aggressivity	Sulfate/sulfide content	BS EN 7755-3-11:1995 (BSI, 1995)
	pH	BS EN 1377-3:1990 (BSI, 1990b)
	Electrical resistivity	
	Organic matter	
Strength	Angle of friction	BS EN 1377-7:1990 (BSI, 1990d)
	Cohesion	
Friability	LA coefficient	BS EN 1097-2:2010 (BSI, 2010b)
Compaction	Maximum dry density	BS EN 1377-4:1990 (BSI, 1990c)
	Optimum moisture content	

Table 1. Standard classification tests undertaken

Figure 4. Photograph of freeze-thaw test chamber

containers to collect outflow water and any fragments passing the (2 mm) mesh size.

Samples of brick were divided into equal weights and hand placed in the containers to ensure that each container had a representative fraction of each grade size. A total of 12 samples were tested, 6 of the red brick, 6 of the yellow. The test specimens were frozen to -15°C , held for a period of 6 h prior to cycling and then subjected to the following cycles

- cooling from 20°C ($\pm 3^{\circ}\text{C}$) to -15°C ($\pm 3^{\circ}\text{C}$) in not less than 20 min and not more than 30 min
- held at -15°C ($\pm 3^{\circ}\text{C}$) for 90–100 min; total freezing period of 120 min (± 5 min)
- thawing from -15°C ($\pm 3^{\circ}\text{C}$) to 20°C ($\pm 3^{\circ}\text{C}$) in not less than 15 min and not more than 20 min; total warm air period of 20 min (± 1 min)
- water spray period shall last 2 min. Following the spray, 2 min were allowed to drain the system.

The above cycles allowed for 10 cycles per day. Half of the test samples were removed after 100 cycles. The remaining samples were tested for a further 100 cycles.

Following completion of the above process, the samples were graded, analysed and post-freezing Los Angeles (LA) tests were undertaken.

3.6 Summary of results and comparison with specification requirements

The results of the pre- and post-freezing grading tests are summarised graphically in Figure 5, with the results of the classification tests summarised in Table 2.

The test results clearly show a difference in behaviour between the two brick stocks found across the site, with significant freeze-thaw effects. In comparison with the yellow stocks, the red stocks had higher sulfate content, lower electrical resistivity, a higher LA coefficient and lower particle density. Each of these differences, and similarities, are discussed in more detail below.

3.6.1 Effect of freeze-thaw on grading

The following observations are made based on the freeze-thaw data from the unsaturated tests presented in Figure 5.

- The greater change in grading of the red bricks for both the 100 and 200 cycle results indicates that the red brick masonry was more susceptible to deterioration during the freeze-thaw process.
- The gradings for both the red and yellow bricks indicated that the freeze-thaw process resulted in a more well-graded fill.
- The gradings show that the majority of the deterioration (typically $>75\%$) occurs during the first 100 cycles.
- With the exception of Yellow Specimen 5 (at 100 cycles), each specimen demonstrated a statistically significant change of grading.

The following observations are made based on the (limited) freeze-thaw tests undertaken in saturated conditions.

- Testing under saturated conditions leads to greater disintegration of the brick particles as compared with testing in air.
- The fines produced were 6% for red and 11% for yellow bricks, which is greater than the fines produced during the tests in air.
- Fractions for the yellow stock samples showed a relatively uniform increase in the percentage of smaller size particles (<32 mm), as compared with the red stock samples that showed a lesser increase for the fractions <16 mm (Table 3).

3.6.2 Sulfate and oxidisable sulfide tests

The red bricks have considerably higher concentrations of water soluble sulfates (SO_4) than the yellow bricks, with measured values of 1300/1200 and 690/590 mg/l, respectively. Both sets of results are high; for example, Poon and Chan (2005) found equivalent values of *c.* 200 mg/l for crushed clay bricks. Moreover, both brick types yielded levels significantly in excess of the upper limit of 300 mg/l for class 6I/6J fill, thereby precluding the potential use of metallic soil reinforcement, or other metallic structural elements within 500 mm of the crushed brick fill.

The sulfate results were below the specified upper limit of 1500 mg/l for materials permitted to be deposited within

Figure 5. Effect of 100 and 200 cycles of freeze–thaw on grading of brick stocks

500 mm of concrete or cement bound materials, although it was noted that the red brick test results were approaching the acceptable limit. Oxidisable sulfide levels were also within the permitted upper limit (0.5%).

3.6.3 pH tests

The red and yellow bricks have similar measured pH values, being 8.6/8.5 for red brick and 8.9 for yellow brick. These results indicate a mildly alkaline composition, probably due to the presence of lime mortar. Both sets of results comply with the class 6I/6J specification limits of between 5 and 10.

3.6.4 Electrical resistivity

Resistivity was measured in order to assess the capability of the soil to carry electric currents and deduce the corrosiveness of the materials. High resistivity results in a low corrosive rate. The investigation carried out included conducting two resistivity tests on each brick type and these showed that the red brick is more corrosive. As-sampled values of $27 \Omega \text{m}$ for the red bricks reduced to $21 \Omega \text{m}$ after saturation for an hour. Comparable values for the yellow bricks were 36 and $46 \Omega \text{m}$ for as-sampled, and 27 and $32 \Omega \text{m}$ after saturation.

For class 6I/6J fill, the SHW specifies a minimum resistivity of $30 \Omega \text{m}$ for material in contact with stainless steel and $50 \Omega \text{m}$ for galvanised steel. The results support the findings from the sulfate testing, that is, that metallic soil reinforcement should not be used with the proposed crushed brick material.

3.6.5 LA tests

The LA tests were conducted in order to determine resistance to fragmentation, and were undertaken before and after freeze–thaw testing to assess its effects. As resistance to fragmentation is indirectly proportional to the LA coefficient, lower coefficients are better.

Before freeze–thaw, coefficients of 65 and 34 were recorded for the yellow brick particles in the size ranges 31.5–50 and 16–31.5 mm, respectively. For the red bricks the equivalent coefficients were 57 and 37. Both sets of data indicate that the larger particles were significantly more susceptible to fragmentation although it should be noted that the LA tests are different for the two fractions. Table 4 shows that the results for the larger particles of both brick types were high compared with natural aggregates, indicating significantly less durability. Results for the smaller particles were more comparable.

Test parameter				Limits (for selected fill types)		
				1A	6I	6J
Particle characteristics						
Particle size distribution (% passing)	125 mm	100%	100%	95–100%	100%	
	75 mm	100%	100%		85–100%	
	63 mm	97%	97%			
	37.5 mm	46%	36%			
	14 mm	17%	15%		25–100%	
	2 mm	8%	7%		15–100%	
	0.6 mm				9–100%	
	0.063 mm			<15%	<15%	
Particle density	Before freezing	2.32	2.37	—	—	—
		2.28	2.38			
	After freezing	2.17	2.20	—	—	—
Aggressivity						
Water soluble sulfate content: mg/l		1300	690	<1500	<300 (GS)	
		1200	590	(RC)	<600 (SS)	
Oxidisable sulfide content: %					<1500 (RC)	
		<0.01	<0.01	<0.5(RC)	<0.06% (GS)	
					<0.12% (SS)	
pH					<0.5% (RC)	
		8.6, 8.4	8.9, 8.9	—	5–10	
Electrical resistivity: Ω m		27	36	—	>50 (GS)	
		27	46		>30 (SS)	
Organic matter: %		<0.1, 0.4	0.6, 0.1	—	<0.2% (GS, SS)	
Strength						
Angle of friction: deg		47.5 (or 54 at low stresses)	32 (or 58 at low stresses)	Specified by design (>36°)		
		15 (or 0 at low stresses)	49 (or 0 at low stresses)	Specified by design		
		19.1	28.3	—		
		ii	>iv	—		
Compressive strength – whole brick: N/mm ²		>6 N/mm ²	<2 N/mm ²			
Mortar designation and strength						
Friability						
LA coefficient		16–31.5 mm fraction		Not specified for types 1A, 6I, 6J fills.		
	Before freezing (1)	37	34	Limits for other similar fills include:		
	Before freezing (2)	31.5–50 mm fraction		1C (general fill) <50		
		53, 61	65, 65	6F1/6F2 (capping) <60		
	After freezing (2)	56	51	6N (structural fill) <40		
				6P (structural fill) <50		
Compaction						
Maximum dry density: kg/m ³		1500	1470	Specified by design		
		9.0	14.5	Specified by design		

Limits related to SHW limits unless identified otherwise. Limits in bold indicate test values outside the limits. GS, galvanised steel; SS, stainless steel; RC, reinforced concrete

Table 2. Summary of test results

Brick type	Sieve size: mm				
	32	16	8	4	2
Red: %	16.6	9.2	6.1	5.1	5.5
Yellow: %	13.5	13.5	12.9	11.8	10.8

Table 3. Increase in % passing specified sieve sizes following freeze–thaw cycling in saturated conditions

Aggregate	LA coefficient
Natural gravel	36
Flint gravel	22
Quartzite gravel	19
Latite basalt	15
Limestone	20–43
Natural granite	27
Dolerite	12–16
Quartz diorite	22
Gritstone	18

Sources: Debieb and Kenai (2008), Indraratna *et al.* (1998) and Smith and Collis (1993)

Table 4. Indicative published values for the LA coefficient

Comparison of the results for the yellow bricks before and after freeze–thaw showed a reduction in coefficient from 65 to 51 for particles in the 31.5–50 mm size range. Although indicating a higher resistance to fragmentation, the results are still high compared with natural aggregates. The effect of freeze–thaw on smaller fractions (BS EN 1097-2:2010 (BSI, 2010b) Annex A test) was not investigated in this trial study but such would be advisable to indicate long-term performance where bricks are due to be crushed to this grading.

In contrast, the equivalent results for the red brick showed only a marginal freeze–thaw effect with respective values of 57 and 56. The red bricks did not indicate a grading change pattern similar to the yellow bricks, possibly because the higher mortar content masked the pattern in the results, or possibly because increased fracturing during the freeze–thaw process had resulted in stronger particles that were more resilient to the LA test.

It is not possible to conjecture with any reliability what the effect of freeze–thaw may have been on finer fractions.

3.6.6 Particle density

The results for the yellow bricks yielded a mean value of 2.38 Mg/m^3 before freeze–thaw, subsequently reducing to

2.20 Mg/m^3 . These were higher than the result for the red bricks of 2.30 and 2.17 Mg/m^3 , respectively. The small reductions in particle density after freeze–thaw testing indicate that the freeze–thaw process has caused the particles to expand without contracting back to the original position, leading to decreases in the particle density.

Typical values of particle density for bricks vary widely with brick type. Hall (1996) suggests a typical density of 2.25 – 2.80 Mg/m^3 . The results for the red and yellow bricks lie at the lower end of this range, indicating perhaps poor compaction, high mortar content and/or low-density inclusions within the bricks.

3.6.7 Shear box strength tests

The study included two shear box tests to obtain indicative values for the effective shear strength parameters for the brick samples. The yellow brick exhibited characteristics different from the red bricks, with the latter having a reported effective cohesion of 15 kPa and an effective angle of friction of 47.5° compared with respective values for the yellow bricks of 49 kPa and 32° . Inspection of the test data indicated that the failure envelopes were not subject to significant scatter, but there was evidence of curvature of the failure envelopes at low stresses. Reanalysis of the test data to derive corrected values for stresses below 50 kPa normal stress, assuming zero cohesion (as typical for this material), yielded friction angles of 54° and 58° for the red and yellow bricks, respectively. The apparent higher strength of the yellow bricks on this basis is consistent with its lower LA values and higher particle density.

There are no upper or lower limits specified in the SHW class 61/6J specification, but Table 5 summarises typical values for some recycled and natural aggregates. The results from this study can be seen to be comparable with previous research.

3.6.8 Compaction test

The compaction tests were carried out in order to determine indicative values for the maximum dry density and optimum moisture content, which may be required for the design of a suitable compaction specification. The maximum dry densities of the red and yellow bricks were similar at 1.50 and 1.47 Mg/m^3 . The optimum moisture content, however, differed with 9.0% for the red brick and 14.5% for the yellow brick. Published values for comparison are limited. However Chidioglou *et al.* (2009) and Steele (2004) both recorded a maximum dry density of 1.79 Mg/m^3 in their separate research, with an optimum moisture content of 7 and 13% (respectively). This suggests that the dry density values reported in this project are possibly low, but this could simply be a reflection of the low particle densities measured.

Aggregate	Friction angle: deg	Source
Crushed brick	57	Chidiroglou <i>et al.</i> (2009)
Crushed demolition waste (primarily brick)	64	Steele (2004)
Crushed demolition waste (concrete)	63	
Sandstone	60	Charles and Watts (1980)
Basalt	60	

Table 5. Indicative effective friction angles for selected recycled and natural aggregates

3.6.9 X-ray diffraction (XRD) analyses

The XRD tests were carried out on the two samples of bricks, thereby allowing some indication to be gained on the variability of the materials. Only small differences in the mineralogy of the red and yellow stocks were recorded, suggesting that there were slight differences in the source of clay used to form the bricks as well as differences in the engineering properties of the bricks probably due to the manufacturing processes.

4. Overview of findings from research study

The research study yielded a range of site-specific quantitative data that could be used within the detailed design and construction process. Key findings were as follows.

- There were significant differences in the properties and susceptibility to freeze–thaw effects of the two types of brick identified at the BDU scheme.
- The more controlled manufacturing process associated with the more recent yellow bricks led to those stocks exhibiting better performance characteristics overall.
- In comparison with the yellow stocks, the red stocks had higher sulfate content, lower electrical resistivity, a higher LA coefficient and lower particle density.
- Both types of crushed brick were found to be susceptible to degradation under freeze–thaw conditions; if uncontrolled this could lead to some long-term settlement of the fill and some reduction of its strength.
- There is evidence that degradation due to freeze–thaw and general performance of the crushed brick improves if the maximum particle size of the grading produced by crushing is reduced. Care needs to be taken though to avoid overprocessing the masonry, as repeated crushing may lead to micro-fracturing and impaired long-term performance.

Overall, the study has shown that with adequate care, controls and design, the BDU crushed brick could be used as a reinforced-earth fill material, where non-metallic soil

reinforcement (e.g. polymeric geogrid) is used. Testing additional to that undertaken as part of the trial would be required to establish the design parameters, and this would need to be supported by validation testing during construction to demonstrate full compliance with the specification.

5. BDU update – current construction works

Following the preliminary design phase (which included this research study), a Design and Build contract was awarded to Skanska in 2012. The detailed design (by Ramboll) adopts the use of crushed brick as a class 6I/6J structural fill within the reinforced-earth structures. Crushed brick is also being proposed for use as a class 6F1/6F2 fill for piling mats and permanent fill beneath the BDU box structure.

As part of an early works package in late 2012/early 2013, the disused ‘Bay Viaduct’ was demolished (Figures 6–7), with the brick waste crushed on site and recycled as a class 6I/6J fill within a 6 m high reinforced-earth road–rail vehicle access ramp (RRV2) (Figure 8). This structure has been successfully handed over to NR and is subject to ongoing monitoring as a condition of design acceptance. Anticipated levels of vertical settlement (<2.5 mm) were recorded during the first 5 months following construction. During 2014, the smaller of the three reinforced-earth railway structures (SS408) was constructed (Figures 9 and 10), albeit with imported 6I/6J material due to the need to construct it in advance of the main viaduct demolition (Figures 11).

The BDU scheme is due to be fully complete in spring 2017. All brick demolition waste from the BDU works (apart from any heavily contaminated material) is planned to be incorporated in the permanent works.

Figure 6. Bay Viaduct (part demolished)

Figure 7. Demolished Bay Viaduct and crushed brick stockpile

Figure 9. Track ballast will be laid above precast trough units (reinforced-earth structure SS408)

Figure 8. Completed reinforced-earth (crushed brick) RRV2

6. Discussion – project innovation

There has been much written on the barriers to innovation within the UK construction activity. These barriers include risk-averse (design, construction and client) teams or organisations, overly onerous ‘standard’ specifications, bespoke nature of projects, resistance to change, lack of motivation and weak leadership. It is suggested that the relatively low levels of innovation are not due to the lack of ideas, but due to the challenges in turning good ideas into practice, and then into common practice.

The BDU crushed brick study is a good example of what can be achieved when there is an all-party motivation to seek to innovate to achieve project goals. It is proposed that the BDU

success in realising the potential for incorporating brick demolition waste within the permanent works was down to three main factors. The first was the early introduction of the idea by the preliminary design team. The second key factor was the motivation of the BDU client project team and the ensuing and necessary engagement and support of not only the various strands that make up the overall client/programme team (i.e. the engineering, project management, environmental and commercial teams) but also the future asset management team. This was primarily achieved by developing a business case for the research study, and defining the potential benefits and risks associated with the proposals to achieve stakeholder buy-in. The third key factor was the design and build team’s willingness to take on and develop the proposals. As a result of this collaborative effort, the demolished viaduct brickwork is being recycled in situ into the permanent works, with a significant reduction in imported fill, exported demolition waste and associated reduced volumes of BDU construction traffic required in this congested part of London.

7. Conclusions

The research study presented and subsequent detailed design and construction works for the Thameslink Programme BDU scheme have demonstrated that with appropriate design and validation testing, crushed bricks can be considered for use as a structural fill material.

The success of the project may be attributed to a high-level policy commitment to sustainability and resource efficiency, backed up by stakeholder engagement and a commitment to invest in research and innovation early in the project that have enabled the opportunities to be realised.

Figure 10. Eastern end of SS408 (reinforced-earth structure) showing precast trough units above modular blockwork wall facing units

Figure 11. New Cross Loop Viaduct (showing part of length to be demolished)

One of the issues restricting innovation in the industry seems to be a lack of published data that would allow those with aspirational ideas to recycle masonry, to assess more confidently the basis of their designs and manage risk. A range of quantitative data for two different types of brick has been reported that others may find useful for preliminary design purposes for their scheme, or for benchmarking their scheme-specific data. Similar publication by others is urged so that the industry can develop a database of collective experience that will reduce the learning curve and innovation risk, and allow the industry to better drive the sustainability agenda.

The work has also afforded some specific engineering learning, which may be summarised as follows.

- There is no single type of brick. Significant differences in behaviour of two types of brick have been measured during this study, and these are considered to stem from differences in the manufacture of the bricks and differences in construction. This highlights the importance of understanding the history of any masonry structure and the range of bricks present. In this case, zoning of the viaducts by age and hence defining the spatial distribution of the brick types was a relatively easy task, but in other situations this may not be as easy.
- Crushed brick as a structural fill should be located away from the frost zone due to its high absorption and potential degradation under freeze–thaw conditions. For the above ground structures such as reinforced-earth structures, geographical position and exposure need to be considered when determining the appropriate frost resistant cover.
- Crushed brick as a structural fill should be located above good drainage material to avoid saturated conditions and associated weakening of the particles. The long-term performance of the material can be enhanced by minimising infiltration by careful drainage design.
- Crushed brick as a structural fill should be located away from the zone of influence of high dynamic loads, to reduce the risk of fragmentation and abrasion.
- The method of crushing and associated grading needs to be considered carefully and trialled to obtain an appropriate fill material. The study highlights the improved resistance to fragmentation resulting from finer gradings, presumably due to the crushing process splitting the particles along weaker planes.
- Careful validation of the properties of the brickwork to be reused is strongly advocated through a suitable trial study supported by robust validation testing during construction. Consideration should be given to freeze–thaw testing in conditions reflective of in-service conditions, in addition to the standard methodology of testing the specimens in saturated conditions. Further testing, specific to the detailed design requirements and type of crusher plant being adopted, is required to validate the incorporation of crushed brick in the permanent works.

Acknowledgements

The authors acknowledge the permission of Network Rail for the publication of this paper. Views expressed by the authors are however their own. They also thank their colleagues in the BDU project team who provided much valuable assistance. The photographs in Figures 2, 6, 7 & 8 were kindly

provided by Skanska. Preliminary (GRIP4) design of the BDU scheme and detailed design of RRV2 was by Tony Gee and Partners. The GRIP5-8 contractor for the BDU scheme is Skanska, with Ramboll as detailed designer. The (GRIP4) crushed brick study was undertaken for Network Rail by Mott MacDonald, with specialist testing by Sheffield Hallam University, site investigation by Birse and classification tests by Testconsult.

REFERENCES

- BSI (1990a) BS EN 1377-2:1990. Methods of test for soils for civil engineering purposes. Classification tests. BSI, London, UK.
- BSI (1990b) BS EN 1377-3:1990. Methods of test for soils for civil engineering purposes. Chemical and electro-chemical tests. BSI, London, UK.
- BSI (1990c) BS EN 1377-4:1990. Methods of test for soils for civil engineering purposes. Compaction-related tests. BSI, London, UK.
- BSI (1990d) BS EN 1377-7:1990. Methods of test for soils for civil engineering purposes. Shear strength tests (total stress). BSI, London, UK.
- BSI (1995) BS EN 7755-3.11:1995. Soil quality. Chemical methods. Determination of water-soluble and acid-soluble sulfate. BSI, London, UK.
- BSI (2003) BS EN 13925-1:2003. Non-destructive testing. X-ray diffraction from polycrystalline and amorphous materials. General principles. BSI, London, UK.
- BSI (2006) BS EN 14475:2006. Execution of special geotechnical works. Reinforced fill. BSI, London, UK.
- BSI (2007) BS EN 1367-1:2007. Tests for thermal and weathering properties of aggregates. Determination of resistance to freezing and thawing. BSI, London, UK.
- BSI (2010a) BS EN 8006-1:2010. Code of practice for strengthened/reinforced soils and other fills. BSI, London, UK.
- BSI (2010b) BS EN 1097-2:2010. Tests for mechanical and physical properties of aggregates. Methods for the determination of resistance to fragmentation. BSI, London, UK.
- BSI (2011) BS EN 771-1:2011. Specification for masonry units. Clay masonry units. BSI, London, UK.
- BSI (2012) BS EN 933-1:2012. Tests for geometrical properties of aggregates. Determination of particle size distribution. Sieving method. BSI, London, UK.
- BSI (2013) BS EN 1097-6:2013. Tests for mechanical and physical properties of aggregates. Determination of particle density and water absorption. BSI, London, UK.
- Charles JA and Watts KS (1980) The influence of confining pressure on the shear strength of compacted rockfill. *Geotechnique* **30**(4): 353–367, <http://dx.doi.org/10.1680/geot.1980.30.4.353>.
- Chidioglou I, O'Flaherty F and Goodwin AK (2009) Shear behaviour of crushed concrete and bricks. *Proceedings of the Institution of Civil Engineers – Construction Material* **162**(3): 121–126, <http://dx.doi.org/10.1680/coma.2009.162.3.121>.
- Debieb F and Kenai S (2008) The use of coarse and fine crushed bricks as aggregate in concrete. *Construction and Building Materials* **22**(5): 886–893.
- HA (Highways Agency) (1994) *Design Manual for Roads and Bridges 4(1): Part 4 HA 68/94 Design Methods for the Reinforcement of Highway Slopes by Reinforced Soil and Soil Nailing Techniques*. HMSO, London, UK.
- HA (2003) *Design Manual for Roads and Bridges 2(1): Part 5 BD 70/03 Strengthened/Reinforced Soils and Other Fills for Retaining Walls and Bridge Abutments*. Use of BS8006: 1995, incorporating Amendment No. 1 (Issue 2 March 1999). HMSO, London, UK.
- HA (2005) *Manual of Contract Documents for Highway Works*. Specification for Highway Works. HMSO, London, UK, vol. 1.
- Hall C (1996) Clay brick. In *Civil Engineering Materials*, 5th edn, (Jackson N and Dhir RK (eds)). Macmillan, Basingstoke, UK, pp. 495–505.
- Indraratna B, Ionescu D and Christie HD (1998) Shear behaviour of railway ballast based on large-scale triaxial tests. *Journal of Geotechnical and Geoenvironmental Engineering* **124**(5): 439–449.
- Laycock E (2002) Ten years of frost testing at Sheffield Hallam University. *Construction and Building Materials* **16**(4): 195–205.
- NR (Network Rail) (2010) *NR/L3/CIV/140/52C Issue 2, Model Clauses for Civil Engineering Works*. Section 52 Earthworks. Network Rail, London, UK.
- NR (2011) *NR/L3/CIV/071 Issue 4, Geotechnical Design*. Network Rail, London, UK.
- NR (2013) *Sustainable Development Strategy. Our Vision and Strategy: A Railway Fit for the Future 2013–2024*. Network Rail, London, UK. <http://www.networkrail.co.uk/browse%20documents/strategicbusinessplan/cp5/supporting%20documents/transforming%20network%20rail/sustainable%20development%20strategy.pdf> (accessed 27/04/2015).
- Poon CS and Chan D (2005) Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. *Construction and Building Materials* **20**(8): pp 578–585.
- Smith MR and Collis L (1993) *Aggregates – Sand, Gravel and Crushed Rock Aggregates for Construction Purposes*, 2nd edn. Geological Society, Bath, UK, Geological Society Engineering Geology Special Publication No. 9.
- Steele DP (2004) *Ground Engineering as Potential End Uses for Recycled and Secondary Aggregates*. Waste & Resources Action Programme, Banbury, UK.