

Use of crushed brick in reinforced earth railway structures

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Citation:

ELLIS, Simon, GOODWIN, Andrew, LAYCOCK, Elizabeth and HIRST, Chris (2016).
Use of crushed brick in reinforced earth railway structures. Proceedings of the
Institution of Civil Engineers. Construction Materials, 169 (2), 93-105. [Article]

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Title: Use of crushed brick in reinforced earth railway structures

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Abstract (200 words)

The Bermondsey Dive-Under Scheme is a key part of the Thameslink Programme which will remove the existing bottleneck that severely limits the number of trains that can pass through London Bridge Station. The scheme involves extensive demolition of 900m of masonry viaduct followed by the construction of 900m of new structures, 200m of reinforced earth structures, and 200m of embankment widening and raising.

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 permanent works. The overarching objective of the study was to seek to reduce the significant volumes of both imported fill and exported demolition material that would be required for the BDU scheme. In addition to the associated sustainability benefits, the significant reduction in lorry movements from London's congested streets would result in significant environmental and safety benefits.

The paper details the sampling and testing of brickwork that was undertaken as part of the study and presents the findings from the study. A synopsis of the properties of the crushed brick and the material requirements for engineered fill is included. The paper also discusses some of the issues associated with introducing innovation within major works programmes.

The Bermondsey Dive Under Scheme is currently under construction and is scheduled for completion in 2017.

(220 words)

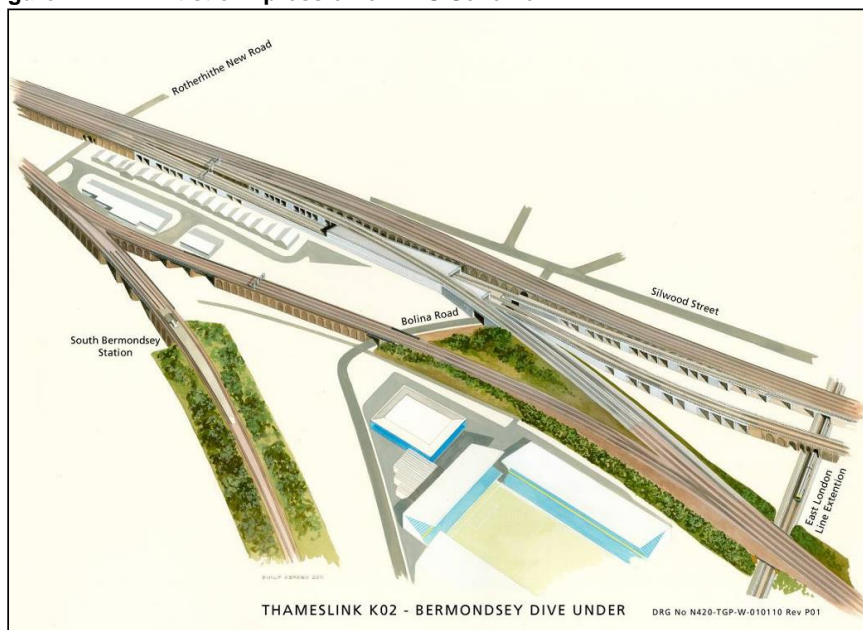
Keywords chosen from ICE Publishing list

Recycling & reuse of materials, Brickwork & masonry, Embankments

1. Introduction

The Bermondsey Dive Under (BDU) scheme (see Figure 1) is a railway project located in the Bermondsey area of South East London that forms a key part of the £6.5 billion Thameslink Programme. This ongoing Programme in South East 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 re-routing four elevated existing lines down through a new box structure that will support the two Thameslink (Fast) Lines above.

Figure 1: Artistic Impression of BDU Scheme



Source: Network Rail (2012g)

To achieve the necessary vertical separation, the scheme involves partial to full demolition of four sections of masonry viaduct totalling approximately 900m incorporating six bridges and a number of retaining structures. The new structures consist of four sections of concrete viaduct (totalling approximately 550m), five bridges, a 135m long concrete box structure, 200m of reinforced earth structures, and approximately 100m of retaining walls. Earthworks include new sections of embankment and raising or re-profiling existing embankments.

As part of the Preliminary Design (GRIP Stage 4), the designer Tony Gee & Partners proposed that where possible, bricks from the demolished viaducts should be reused or recycled in the permanent works (Tony Gee & Partners, 2012a). As the likely performance of the crushed brickwork was not known, Network Rail 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 (SHU) 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 a research trial undertaken to validate the potential use of site-won crushed brick as part of the BDU scheme. 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 Network Rail (NR) places sustainable development at the heart of its culture (Network Rail 2013a). In practical terms for this project, the Thameslink Programme Sustainable Development Policy (Network Rail 2013b) required delivery of sustainable solutions that represented value for money within the available budget and increased resilience to future changes in the 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 lead 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 construction design and planning for the BDU through the design drivers set out by NR and captured through the GRIP4 Stage Site Waste Management Plan (Tony Gee & Partners, 2012b). Based on the BRE SMARTWaste Template, the Plan identified at its highest level the re-use 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 12500m³ of potential masonry waste would be generated, which afforded a potential to reduce waste disposal related lorry journeys from circa 1000 to 100 if recycling was achieved on site.

2.2 Design Requirements

Network Rail requirements for reinforced earth embankments and structures are included in Network Rail NR/L3/CIV/071 'Geotechnical Design', and Network Rail NR/L3/CIV/140/52 'Model Clauses for Civil Engineering Works - Model Clause 052C: Earthworks'. Key requirements relevant to the specific use of crushed brick include:

- The design, materials specification and construction methods adopted for earthworks for reinforced soil and anchored earth structures shall be in accordance with Highways Agency BD 70/03.
- Reinforced soil and anchored earth structures shall be designed to BS 8006 and Highways Agency HA68/94.
- Acceptable material for use as general granular fill shall comply with the requirements for Classes 1 and 3 of Table 6/1 of the Highways Agency Specification for Highway Works (SHW).
- Fill to reinforced soil shall be Class 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 8006-1:2010 as amended by Highways Agency 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 include:

- Fill material for reinforced earth structures should be selected frictional fill (Class 6I/6J for granular frictional fill), though non-standard fills may be used with increased frequency of testing.

- Where metallic soil reinforcement (or other metallic elements) are to be installed, fills shall meet the electro-chemical limitations given in BS EN 14475:2006.
- Friable fill material (i.e. material that 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.

Reference is also made to BS EN 14475:2006: 'Execution of special geotechnical works – Reinforced fill'. This standard 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 guidance states that degradable fill materials should not be used unless specific validation studies are carried out, and material not frost 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) consisted 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 using the SHW as a type 6I/6J free draining granular material with a minimum ϕ' of 36°. Outer 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 2 below.

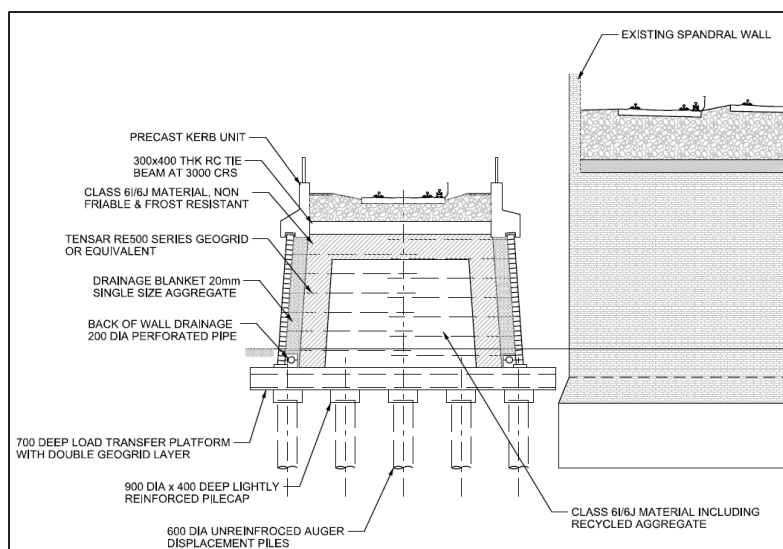


Figure 2: Preliminary Design detail for typical Reinforced Earth Structure

Source: Reproduced from Network Rail (2012g)

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
- Class 6N free draining fill behind retaining walls

- Lightweight fill (maximum unit weight of 5 kN/m³) for raised railway embankments

The use of crushed brick as, or as part of, the Class 1A and 6l/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 permanent BDU works, as proposed by the preliminary design team. The output from the study was to be a report that would provide Network Rail 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 for the study was the high-volume, more structurally demanding Class 6l/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 wall are likely to be well drained, indicating 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 the track loads and to ensure facings were serviceable, but previous research (eg Chidioglou, 2007) indicated relatively high values were likely; as a result it was agreed that compressibility and permeability tests would not be undertaken though such may need to be undertaken by the successful contractor to manage their risks.
- The proposed use of the fill in an elevated and relatively exposed position could promote frost penetration to significant depth, indicating that one focus of the testing should be the durability of the brick under freeze-thaw conditions.
- Classification, compaction and shear strength data would be required for the specification of the 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

Sufficient core material to allow testing different parts of the viaduct independently and indicate spatial variations was not available without substantial programme delays. Hence it was agreed to broadly characterise the red and yellow stocks using a single target grading for each, i.e. a grading compliant with the requirements for 6l/6J fill.

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 (SHU) and weighed,

logged and photographed. Examination of the cores and 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 1840's which had high mortar contents and were irregular in shape; and 'yellow' stocks from the late 1800's viaducts which had a low mortar content and were noted to be broadly consistent in size and shape. Approximately 60kg of core sample for each type of stock was provided.

Following description of the cores, trials were undertaken at SHU 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 5mm being adopted to minimise losses due to fines generation. After the primary crushing cycle, grading tests on the aggregate produced were carried out according to BS EN 933-1 (2012). Secondary crushing was deemed necessary to increase conformity with 6l/J grading; this was restricted to particles retained on the 63mm sieve to minimise the effect of apparent aggregate durability increase with repeated crushing, as highlighted in literature. The grading produced was still not fully compliant with the 6l/J requirements and the red and yellow brick samples had significantly different gradings to each other. The yellow stock material retained on the 63mm 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 6l/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.

Table 1: Standard classification tests undertaken

Fill Property	Test parameter	Test Standard
General	Bulk density	BS 1377-2:1990
	Moisture content	
Particle characteristics	Mineralogy (xray diffraction)	BS EN 13925-1:2003
	Particle size distribution	BS EN 933-1:2012
	Particle density	BS EN 1097-6:2000
Aggressivity	Sulphate/sulphide content	BS 7755-3.11:1995
	pH	BS 1377-3:1990
	Electrical resistivity	
	Organic matter	
Strength	Angle of Friction	BS 1377-7:1990
	Cohesion	
Friability	Los Angeles coefficient	BS EN 1097-2:2010
Compaction	Maximum dry density	BS 1377-4:1990
	Optimum moisture content	

Comment [EL1]: this is the only EN I could find that deals with XRD

AG Not sure which you used Liz – can you find out for the final version (ie after comments back on the submitted draft)

3.5 Freeze/Thaw Testing

Freeze-thaw testing was undertaken in a specialist chamber at SHU (see Figure 1) and broadly followed the standard test method given in EN 771-1:2011.

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. A limited number of freezing tests under the saturated conditions specified in BS EN 1367-1:2007 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 containers to collect outflow water and any fragments passing the (2mm) mesh size.

Figure 1 Photograph of test chamber



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° , held for a period of 6 hours 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 minutes and not more than 30 minutes
- held at -15°C ($\pm 3^{\circ}\text{C}$) for 90 to 100 minutes (total freezing period should be 120 minutes (± 5 minutes))
- thawing from -15°C ($\pm 3^{\circ}\text{C}$) to 20°C ($\pm 3^{\circ}\text{C}$) in not less than 15 minutes and not more than 20 minutes. Total warm air period should be 20 minutes (± 1 minute)
- water spray period shall last 2 minutes. Following the spray, 2 minutes will be allowed to drain the system

The above cycles allowed for 10 cycles per day, running 24 hours. 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 tests were undertaken.

3.6 Summary of Results and Comparison with Specification Requirements

The results of the classification tests are summarised in Tables 2 and 3 below, with the results of the pre- and post-freezing grading tests summarised graphically in Figure 2.

The test results show clearly 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 sulphate content, lower electrical resistivity, a higher Los Angeles coefficient, and lower particle density. Each of these differences, and similarities, are discussed in more detail below.

Effect of Freeze-Thaw on Grading

The following observations are made based on the freeze-thaw data from the unsaturated tests presented in Figure 2:

- 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 indicate that particles retained on sieves 32mm and above are relatively stable.
- Grading curves for the red bricks implied that those particles retained on a 32mm sieve were more stable than those passing

With the exception of Yellow Specimen 5 (at 100 cycles), each specimen demonstrated a statistically significant change of grading.

Comparison with the limited tests undertaken in saturated conditions indicated the following:

- The red and yellow bricks show progressive divergence of the grading curves over the full size range, in contrast to the tests in air which showed a divergence typically from the 32mm sieve size.
- The fines produced were 6% for red and 11% for yellow bricks, which is greater than the fines produced during the tests in air.

Table 2 Overall Increase in Percentage Passing Specified Sieve Sizes Following Freeze-Thaw Cycling in Saturated Conditions

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

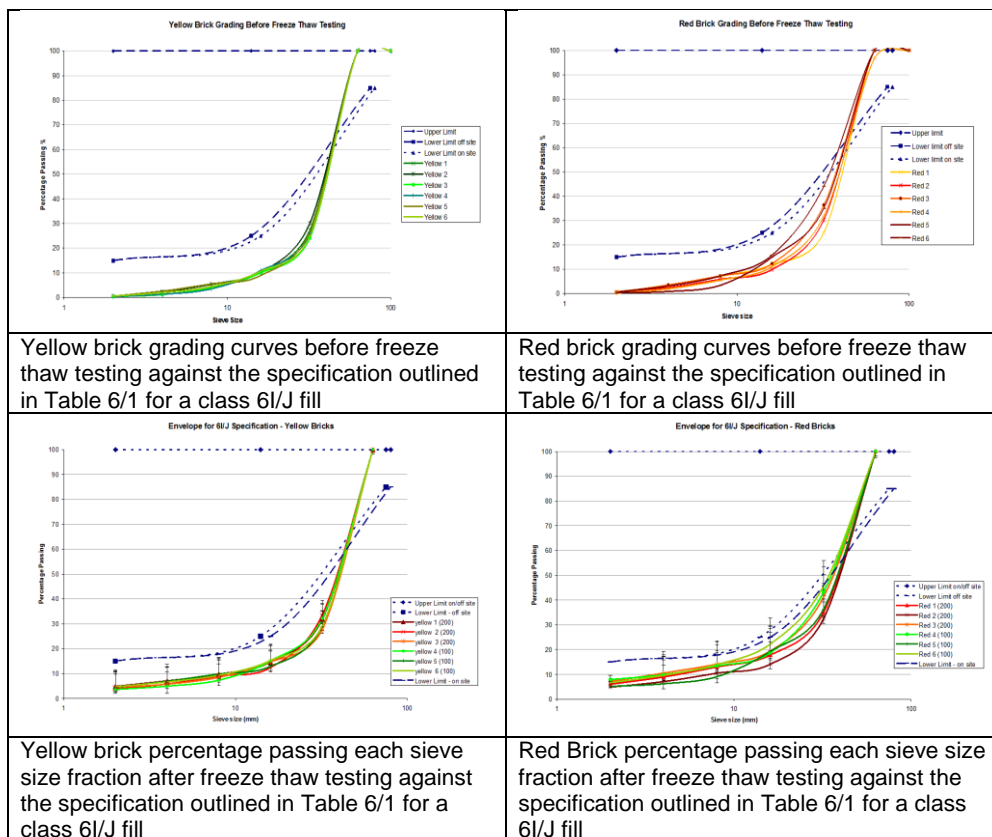
The results in Table 3, though limited, suggest that the crushed bricks will suffer more degradation under freeze-thaw conditions (as BS EN 1367_1:2008) when saturated than when in air. Differential performance of composites of brick and mortar concurs with findings for differential masonry degradation linked to brick and mortar combinations noted in Laycock (2002).

Table 3: Summary of Test Results

Test parameter		Red Brick	Yellow Brick	Limits		
				1A	6I	6J
Particle characteristics						
Particle size distribution (% passing)	125mm	100%	100%	95-100%	100%	
	75mm	100%	100%		85-100%	
	63mm	97%	97%			
	37.5mm	46%	36%			
	14mm	17%	15%		25-100%	
	2mm	8%	7%		15-100%	
	0.6mm				9-100%	
	0.063mm			<15%	<15%	
Uniformity coefficient	Before freezing	3.14	2.57	>10	>10	5-10
	After freezing			>2 (NR specification)		
	After freezing	8.62 ₁₀₀ 9.20 ₂₀₀	4.60 ₁₀₀ 4.98 ₂₀₀	-	-	-
Particle density	Before freezing	2.32	2.37	-	-	-
		2.28	2.38			
	After freezing	2.17	2.20	-	-	-
Aggressivity (GS = galvanised steel, SS = stainless steel, RC = reinforced concrete)						
Water soluble sulphate content, mg/l		1300 1200	690 590	<1500 (RC)	<300 (GS) <600 (SS) <1500 (RC)	
Oxidisable sulphide content, %		<0.01	<0.01	<0.5(RC)	<0.06% (GS) <0.12% (SS) <0.5% (RC)	
pH		8.6, 8.4	8.9, 8.9	-	5-10	
Electrical resistivity, Ωcm		2700 2700	3600 4600	-	>5000Ωcm (GS) >3000Ωcm (SS)	
Organic matter, %		<0.1,0.4	0.6,0.1	-	<0.2% (GS, SS)	
Strength						
Angle of Friction (degrees)		47.5 (or 54 at low stresses)	32 (or 58 at low stresses)	Specified by design (>36°)		
Cohesion (kPa)		15 (or zero at low stresses)	49 (or zero at low stresses)	Specified by design		
Compressive strength - whole brick, (N/mm ²)		19.1	28.3	-		
Mortar designation & strength		ii >6N/mm ²	>iv <2N/mm ²	-		
Friability						
Los Angeles coefficient (1) Annex A test (2) Annex G test	Before freezing (1)	16-31.5mm fraction		Not specified for Type 1A, 6I, 6J fills. Limits for other similar fills include: 1C (general fill) <50 6N (structural fill) <40 6P (structural fill) <50		
		37	34			
	Before freezing (2)	31.5-50mm fraction				
		53, 61	65, 65			
	After freezing (2)	56	51			
Compaction						
Maximum dry density (kg/m ³)		1500	1470	Specified by design		
Optimum moisture content, %		9.0	14.5	Specified by design		

Note: Limits related to SHW limits unless identified otherwise. Limits in bold indicate test values outside the limits.

Figure 2: Effect of 100 and 200 Cycles of Freeze-Thaw on Grading of Brick Stocks



Sulphate and Oxidisable Sulphide Tests

The red bricks have considerably higher concentrations of water soluble sulphates (SO_4) than the yellow bricks, with measured values of 1300/1200mg/l and 690/590mg/l respectively. Both sets of results are high; for example Poon and Chan (2005) found equivalent values of circa 25mg/l for crushed clay bricks. Moreover, both brick types yielded levels significantly in excess of the upper limit of 300mg/l for Class 6I/J fill, thereby precluding the potential use of metallic soil reinforcement, or other metallic structural elements within 500mm of the crushed brick fill.

The sulphate results were below the specified upper limit of 1500mg/l for materials permitted to be deposited within 500mm of concrete or cement bound materials, although it was noted that the red brick test results were approaching the acceptable limit. Oxidisable sulphide levels were also within the permitted upper limit (0.5%).

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/J specification limits of between 5 to 10.

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

(Chance, 2003). 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 $36\Omega\text{m}$ and $46\Omega\text{m}$ as-sampled, and $27\Omega\text{m}$ & $32\Omega\text{m}$ after saturation.

For Class 6l/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 red brick material failed both criteria for all tests, again demonstrating its unsuitability to be deposited near exposed metallic elements. In contrast, considering the resistivity results in isolation, the yellow brick material indicated it would be marginally acceptable in contact with stainless steel, but not galvanised steel. Following saturation its suitability for use in conjunction with stainless steel became marginal.

Los Angeles Tests

The Los Angeles (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 31.5mm to 50mm and 16mm to 31.5mm respectively. For the red bricks the equivalent coefficients were 57 and 37. Both sets of data show that the larger particles were significantly more susceptible to fragmentation. 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..

Comparison of the results for the yellow bricks before and after freeze thaw showed a reduction in the coefficient from 65 to 51 for particles in the 31.5mm to 50mm size range. Though indicating a higher resistance to fragmentation the results are still high compared with natural aggregates. The effect of freeze-thaw on smaller fractions was not investigated in this trial study but such would be advisable to validate the long term performance of bricks crushed and selected to achieve a maximum particle size of say 31.5mm.

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 similar grading change pattern to the yellow bricks, possibly because the higher mortar content masked the pattern in the results, and hence it is not possible to conjecture with any reliability what the effect of freeze-thaw may have been on finer fractions.

Table 4: Indicative Published Values for the LA Coefficient

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), Smith et al (1993)

Particle Density

The results for the yellow bricks yielded a mean value of 2.38Mg/m^3 before freeze thaw, reducing to 2.20Mg/m^3 after. These were higher than the result for the red bricks of 2.30Mg/m^3 and 2.17Mg/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. Jackson & Dhir (1988) suggest a typical density of 2.25 to 2.8Mg/m³. 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.

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 different characteristics to the red bricks, with the latter having an effective cohesion of 15kPa and an effective angle of friction of 47.5° compared with respective values for the yellow bricks of 49kPa 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 which lead to the high cohesion values recorded. Re-analysis of the test data to derive corrected values for stresses below 50kPa normal stress, assuming zero cohesion, 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 6I/J specification, but Table 5 summarises typical values for natural aggregates after Waltham (2009). Comparison of the results indicates both brick types yielded high values, which is consistent with a value of 57° published by Chidiroglou et al (2009) for crushed brick. If the low stress effect is ignored the strength is comparable with natural materials, but the cohesions are very large.

Table 5: Indicative Effective Friction Angles for Natural Aggregates

Aggregate	Friction Angle (°)
Granite	55
Basalt	50
Greywacke	45
Sandstone	45
Limestone	35
Mudstone	30
Shale	25

Source: Waltham (2009)

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 Mg/m³ and 1.47 Mg/m³ however the optimum moisture content was 9.0% for the red brick and 14.5% for the yellow brick. Published values for comparison are limited. However Chidiroglou (2007) recorded a maximum dry density of 1.79Mg/m³ in his research, with an optimum moisture content of 7%. 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.

X-Ray Diffraction (XRD) Analyses

The XRD tests were carried out on Batch A and Batch B samples, 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:

- 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 younger yellow bricks lead to those stocks exhibiting better performance characteristics overall.
- In comparison with the yellow stocks, the red stocks had higher sulphate content, lower electrical resistivity, a higher Los Angeles coefficient, and lower particle density.
- Degradation of both types of crushed brick under freeze-thaw conditions was shown to be likely, which 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 over-processing the masonry, as repeated crushing may lead to micro-fracturing and impaired long term performance.

Overall the study showed 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 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 research study, which was undertaken during the preliminary design phase, a Design and Build contract was awarded to Skanska in 2012. The detailed design was subsequently developed by Ramboll and successfully incorporated the use of crushed brick as a Class 6I/6J structural fill within the reinforced earth structures. It included also use of crushed brick 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 3 and 4), with the brick waste crushed on site and recycled as a Class 6I/6J fill within a 6m high reinforced earth Road-Rail Vehicle access ramp (RRV2) (Figures 5 and 6). This structure has been successfully handed over to Network Rail and is subject to ongoing monitoring as a condition of design acceptance. During 2014 the smaller of the three reinforced earth railway structures (SS408) was constructed, albeit with imported 6I/6J material due to need to construct in advance of the main viaduct demolition (Figures 9 and 10).

Satisfyingly for all concerned, apart from any heavily contaminated material, all brick demolition waste from the BDU works is planned to be incorporated in the permanent works. The BDU scheme is due to be fully complete in spring 2017.

Comment [CSE2]: Have moved BDU update and management conclusions to new sections below conclusions to improve flow/readability.

AKG Sorry Simon but I think we need to keep to the usual paper format which includes a clear conclusion. As you changed it we lost that. I have re-structured it again and changes the headings / text slightly throughout to make the whole flow, including your virtually unchanged inserts.

Comment [ST3]: Simon - did you get any info from them on how they utilised the study? On additional testing they undertook? It would be good to add just a few sentences showing how the design built on the research study.

Comment [ST4]: NOT REFERRED TO FIG 7 & 8 - NEEDED?



Figure 3: Bay Viaduct (part demolished) (Skanska)



Figure 4: Demolished Bay Viaduct and crushed brick stockpile (Skanska)



Figure 5: RRV2 under construction (with crushed brick fill) (Skanska)



Figure 6: Completed RRV2 (Skanska)



Figure 7: Eastern end of BDU site (Skanska)



Figure 8: New Cross Loop Viaduct (to be demolished)

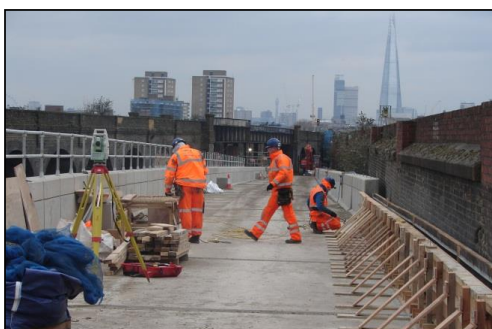


Figure 9: SS408 (Reinforced earth structure)



Figure 10: SS408 (Reinforced earth structure)

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 (Maqsood et al, 2003). 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 a motivation to seek to innovate to achieve project goals. It is proposed that the BDU success in realising the potential for incorporation 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 teams' willingness to take on and develop the proposals. As a result of this collaborative effort, the demolished viaduct brickwork is being recycled insitu 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 combined with the subsequent detailed design and construction works for the Thameslink Programme Bermondsey Dive Under scheme have demonstrated that crushed bricks may be used not just as general engineered fill but also as structural fill where performance is critical. The success of the project may be attributed to a high level policy commitment to sustainability and resource efficiency, backed up by a commitment to invest in research and innovation early in the project to ensure the effective implementation of the drivers.

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 more confidently assess 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 our collective experience that will reduce the

learning curve and innovation risk, and allow the industry to better drive the sustainability agenda.

The work has afforded too 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 quantifying the mass of each brick type on any specific pproject. 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 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
- 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 carefully considered 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 re-used is strongly advocated through a suitable trial study supported by robust validation testing during construction. Such should include freeze-thaw testing in conditions reflective of in-service conditions, which may mean deviating from the standard methodology of testing the specimens in a saturated condition. 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 works

Acknowledgements

The authors would like to acknowledge the permission of Network Rail for the publication of this paper. Views expressed by the authors are however their own. They would also like to thank their colleagues in the BDU project team who provided much valuable assistance.

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 Test Consult.

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