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Optimum water content tests for earthen construction materials

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There is considerable interest in earthen construction materials, owing to their inherent sustainability, and also in the conservation of heritage structures. For new-build in situ construction a key aspect of quality control is the achievement of full compaction to maximum dry density. At present the guidance available in this area to those using these materials varies from British Standard tests to heuristic-based methods developed by practitioners. In this paper, the various tests are compared for different soil mixes and also to judge the influence of the test operator. The study demonstrates shortcomings in the heuristic methods and indicates that, for modern standards of quality control to be achieved, alternative tests should be used.

Notation

R^2	coefficient of determination
w	water content
w_{opt}	optimum water content
ρ_{d}	dry density
ρ_{dmax}	maximum dry density

1. Introduction

Earthen construction techniques can be separated into two different classes: unit based and in situ construction, both of which have a long history of use by man and are attracting much interest currently owing to their potential low impact. Rammed earth (RE) is one of the most significant in situ earthen construction techniques, with a long history dating back over 4000 years. With growing concerns over climate change and rising energy costs the importance of using low-carbon materials, such as RE, within the built environment is ever increasing (Houben and Guillaud, 1989; Jaquin *et al.*, 2008). The RE construction process involves placing layers of wet mixed and selected subsoil within formwork, similar to that found in concrete construction. Each layer is then compacted on top of the previous layer using a pneumatic rammer before the formwork is removed, revealing a continuous load-bearing wall. The wet RE is then left to dry naturally and reaches full strength once the entirety of the wall has dried to the ambient conditions (Houben and Guillaud, 1989; Walker *et al.*, 2005). When compacting any soil mixtures comprising a range of particle sizes the water content (w) is an important factor determining the final density of the material achieved and, for any given compactive effort, an optimum water content (w_{opt}) exists where the maximum dry density (ρ_{dmax}) will be achieved (Al-Shayea, 2001; Cetin *et al.*, 2007; Ruiz *et al.*, 2005; Seo *et al.*, 2008). Therefore, water content of the soil mixture used in RE is similarly an important variable in ensuring maximum density and hence strength (Houben and Guillaud, 1989; Keable, 1996; Walker *et al.*, 2005).

The drop test (DT) is the currently accepted method for the on-site testing of w_{opt} for soils used in RE; however, it has no definitive procedure and different descriptions are given for the procedure by Easton (2007), Houben and Guillaud (1989), Keable (1996), King (1996) and Walker *et al.* (2005). The basic principle of the DT involves dropping a ball of RE from a known height and then using the way in which the ball breaks on impact with the ground to determine if the RE is at optimum, or not, and relies largely on the subjective opinion of the test operator to decide when w_{opt} is achieved. Maniatidis and Walker (2003) also note, following interviews of building contractors involved in RE building projects across the UK, that experienced builders assess the water content by feel and observation alone. In conventional soil mechanics, British Standard BS1377: 1990 (BSI, 1990) provides three tests to obtain the relationship between dry density ρ_{d} and water content w for a given soil: the light manual compaction test (LMCT), heavy manual compaction test (HMCT) and the vibrating hammer test (VHT). All three methods provide a value of w_{opt} specific to the amount of compactive effort used and BS1377 expects that the method used to determine the w_{opt} in the laboratory will most closely match the final compaction technique being implemented on site (BSI, 1990).

This paper investigates which, if any, of the currently used BS1377 soil classification tests and on-site DTs return a w_{opt} value similar to the on-site w_{opt} value required to compact RE to its ρ_{dmax} within formwork using a pneumatic rammer (the normal means of compacting RE). In the next section the experimental procedure is described, in Section 3 the results are discussed and conclusions are drawn in Section 4.

2. Experimental procedure

The experimental programme was divided into three sub-investigations: the first established the w_{opt} for RE when compacted close to on-site conditions. The second investigated the BS1377 laboratory tests to determine which test returned a w_{opt} most similar to that on site, whereas the third covered the on-site DT methods, specifically looking at the effects of different operators performing the DT and the repeatability of the DT with multiple RE mixes. In order to investigate the DT procedure, as a general test, two different DT methods were selected, namely the procedure described by Houben and Guillaud (1989) (HGDT) and that described by Walker *et al.* (2005) (WDT). The two DTs differ in terms of the height from which the RE is dropped (waist and shoulder), but are otherwise similar to one another as both tests use fist-sized (40–50 mm) soil samples and use the number of pieces into which the lump breaks to decide whether the RE is at optimum. The two DTs chosen are, for the remainder of this document, referred to as HGDT and WDT respectively.

In addition to the water content at compaction, the quantities of the individual components, that is the clay, sand and gravel, have an important influence on the final strength and quality of the RE wall (Beckett, 2011; Houben and Guillaud, 1989). Hall and Djerbib (2004) propose a soil mix naming method, which is used here, based on the masses of sand, gravel and silty clay components, respectively, where a soil mix classed 712 contains 70% sand, 10% gravel and 20% silty clay. Five RE mixes were used during the experiments, 514, 523, 613, 622 and 712, and all fall within the limits for RE construction provided by Houben and Guillaud (1989). Figure 1 shows the particle grading for each of the five RE mixes.

The RE mixes were all manufactured in the laboratory by combining the appropriate amounts of dried Birtley clay, sharp sand and pea gravel. The Birtley clay was oven dried at 105℃ before being pulverised and passed through a 2·36 mm sieve. Both the sharp sand and the pea gravel were also oven dried at 105℃ and then passed through 2·36 mm and 10 mm sieves respectively. Between each sub-investigation, and also between tests for sub-investigation 1, the RE mixes needed to be dried and returned to their pre-compacted state. This procedure is given in Table 1.

2.1 Investigation 1: On-site optimum water content

In order to compare laboratory results with real life situations it was necessary to obtain the w_{opt} for a RE wall constructed on site. The investigation used a pneumatic rammer to compact 305 mm by 150 mm by 150 mm samples of all five RE mixes at six target water contents, 5·0, 6·5, 8·0, 9·5, 11·0 and 12·5%.

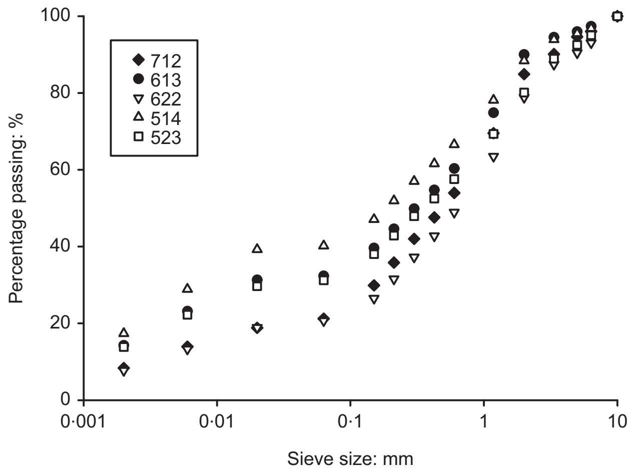

Figure 1. Particle grading curves for all RE mixes

The following procedure is referred to here as the on-site equivalence test (OSET) and was designed to determine ρ_{dmax} and w_{opt} for each RE mix. The procedure is presented in Table 2.

Having calculated the volume and the water content of each of the RE blocks, the bulk and dry densities obtained at each water content were calculated. Plotting the ρ_d against w then enabled a line of best fit to be drawn and the w_{opt} and ρ_{dmax} could be found at its peak.

2.2 Investigation 2: British Standard test verification

In order to determine if any of the three methods outlined in the BS1377 procedures (BSI, 1990) produced an w_{opt} value close to the on-site w_{opt} for RE, all three tests – HMCT, LMCT and VHT – were performed on all five RE mixes at six target water contents. A full description of each of the three methods can be found in BS1377-4 (BSI, 1990) and a summary of the entire procedure is presented in Table 3. Each of the five RE mixes was split into three sub-samples (of approximately 6·5 kg) and the procedure was performed on all three sub-samples. The procedure was designed to obtain results for all three of the BS1377 tests at six target water contents, 5·0, 6·5, 8·0, 9·5, 11·0 and 12·5%, for each sub-sample.

The bulk and dry densities of each of the RE samples, for each target water content, were then calculated, the ρ_d against w were plotted and a line of best fit was drawn. As stated in the BS1377 procedures (BSI, 1990) the w_{opt} and ρ_{dmax} were then taken as the peak in the plotted curve.

2.3 Investigation 3: Drop test verification

Two separate experiments were performed to establish the effectiveness of the DT: an investigation into the reliability of

	Description
1	The RE is placed within a metal tray and oven dried at 105°C for 48 h
2	The dried RE is then broken into constituent parts using a pneumatic rammer, protected by a rubber mat to prevent the altering of the sand, clay and gravel structures
3	The dry mix is then passed through a 10 mm sieve to ensure the maximum particle size is still achieved

Table 1. Procedure for returning a RE mix to its original state

the DT with respect to the operator carrying out the test, and an investigation into the ability of the DT to return an optimum result for different RE mixes. Both procedures investigated all five RE mixes and compared the w_{opt} results returned with the OSET results.

2.3.1 Investigating the effect of the operator

To investigate the effect of the operator, 50 undergraduates were asked to provide a sample of RE at what they deemed to be w_{opt}, following the WDT procedure. Undergraduate civil engineers were used to perform the role of test operators because engineering students, who all perform laboratory work as part of their studies, should be able to follow instructions to a sufficient standard such that inaccuracies in following a method would not occur. The students were also unlikely to have encountered RE, and hence the DT, because of the lack of use of RE in mainstream engineering. The other variable that was thought may have an impact on the result was the operator height, so this was also recorded for each operator. Because it was assumed that the operators had no knowledge of RE, or of adjusting water content within a soil, and there was insufficient time to allow the RE to dry if made too wet, a large surplus of below w_{opt} RE mix was required for operators to return to if they felt the RE mix they had made was too wet.

The experiment involved five groups of ten students and each group used a different RE mix. Before the experiment each operator was provided with the following: written instructions of the Walker *et al.* (2005) DT procedure; a metal tray containing 1 kg of prepared RE mix at $w = 4\%$; water to increase w for the RE mix; and a numbered sample tray, to provide a water content sample at the end of the test. At the start of the experiment the group was read an introductory script that provided them with some background into RE, and more specifically the need for the DT. The operators was asked to perform the test, increasing the water content as they felt necessary, and to provide a sample of RE that they believed was at w_{opt}. If the operator, at any point, felt that their sample was too wet, they were asked to provide a sample (of approximately 100 g) and then they were given 100 g more 4% RE to return the mix to a drier condition. After the experiment, the sample of RE that the operator had classified as optimum was then analysed to determine its w.

2.3.2 Investigating the effect of the RE mix

To investigate the differences between the two DT methods and also the effect of the RE mix on the results, the first author performed the DT under controlled laboratory conditions at a range of water contents between 5 and 13%. Owing to the expected variability of the results obtained, it was decided that even obtaining DT w_{opt} results for each RE mix in triplicate was unlikely to be sufficient. Therefore, each of the RE mixes was tested on three separate occasions and on each occasion each DT was performed for each water content three times. This produced nine different verdicts produced by each DT for any given target w within the scope of the experiment. All five

	Description
1	Water is added to the RE mix (approximately 13 kg dry) to achieve the first target *w*
2	The RE is placed in a mould (305 mm by 150 mm by 200 mm deep) to a depth of 150 mm
3	The sample is compacted for 60 s using the pneumatic hammer. This is sufficient time for a ringing noise to be heard, which is used on site to indicate full compaction (Walker *et al.*, 2005)
4	The depth to the RE surface is measured in six positions and averaged to obtain the volume of the compacted RE block
5	The block is removed from the mould and weighed on the double scale arrangement (rated to 20 kg $\pm$ 2 g)
6	Three samples of the RE block are taken to determine the true *w*
7	The block is then broken down, returned to the RE mix and water is added to reach the next target *w*
8	Steps 2 to 7 are repeated for all six target *w* values

Table 2. OSET procedure

	Description
1	Water is added to the RE mix (approximately 6·5 kg dry) to achieve the first target *w*
2	The LMCT is performed for the single water content, in which the mass is recorded and the actual *w* is determined
3	The sample is broken down and returned to the remaining mix
4	The HMCT is performed for the single water content, in which the mass is recorded and the actual *w* is determined
5	The sample is broken down and returned to the remaining mix
6	The VHT procedure is performed for the single water content, in which the mass is recorded and the actual *w* is determined
7	The block is then broken down, returned to the RE mix and water added to reach the next target *w*
8	Steps 2 to 7 are repeated for all six target *w* values

Table 3. British Standard test verification procedure

RE mixes were investigated at nine target water contents, 5·0, 6·0, 7·0, 8·0, 9·0, 10·0, 11·0, 12·0 and 13·0%. The detailed procedure is presented in Table 4.

3. Results

3.1 Investigation 1: On-site optimum water content

For all five RE mixes investigated it was possible to determine a range of water contents in which the RE material can be considered at its w_{opt} for on-site construction. Fifteen complete OSETs were performed, involving 90 individual values of w and ρ_d. Figure 2 shows five examples of the complete w–ρ_d plot produced by single OSETs for each of the RE mixes.

Two OSET results were deemed anomalous and the remaining two results were used to produce the range and average of on-site w_{opt} values. The 514 RE result is a clear outlier as the ρ_{dmax} values for all three results have a percentage difference less of 0·38%, whereas the w_{opt} has a percentage difference of 17·55% when the anomalous result is included but only 2·34% when it is omitted. The 613 RE result was omitted because the curve plotted had a much lower coefficient of determination R^2 than the other two results (0·86 as opposed to 0·99 and 0·93).

The primary aim of this sub-investigation was to establish the w_{opt} for the five RE mixes when being compacted on site. Because the compactive effort applied to a material directly affects its w_{opt}, these results cannot be taken as a universal set of values for the corresponding mixes; however, the values obtained using the OSET provide a good comparison to enable the analysis of the currently used w_{opt} determination methods. The w_{opt} values obtained in this sub-investigation are not identical, because the process by which a RE wall is constructed is not a perfectly controllable procedure; therefore, a range of water content values, which are to be regarded as optimum, are proposed. Table 5 presents these values for each RE mix, and these values of w are taken as at optimum for on-site compaction throughout the remainder of the paper; they also act as the basis for the critical assessment of the currently used w_{opt} determination methods.

	Description
1	Water is added to the RE mix (approximately 6·5 kg dry) to achieve the first target *w*
2	The HGDT is performed dropping the RE ball onto a grid marked board
3	A photograph is taken to record the result, an approximate number of pieces is counted and the verdict is recorded (i.e. too wet, too dry or optimum)
4	Steps 2 and 3 are repeated twice more to produce triplicate results for the same *w*
5	A sample of the RE mix is taken to establish the true *w*
6	The WDT is performed dropping the RE ball onto a grid marked board
7	A photograph is taken to record the result, an approximate number of pieces is counted and the verdict is recorded (i.e. too wet, too dry or optimum)
8	Steps 6 and 7 are repeated twice more to produce triplicate results for the same *w*
9	Water is added to increase the RE mixes *w* to the next target value
10	Steps 2 to 9 are repeated to provide results for all nine target *w* values

Table 4. Drop test verification procedure

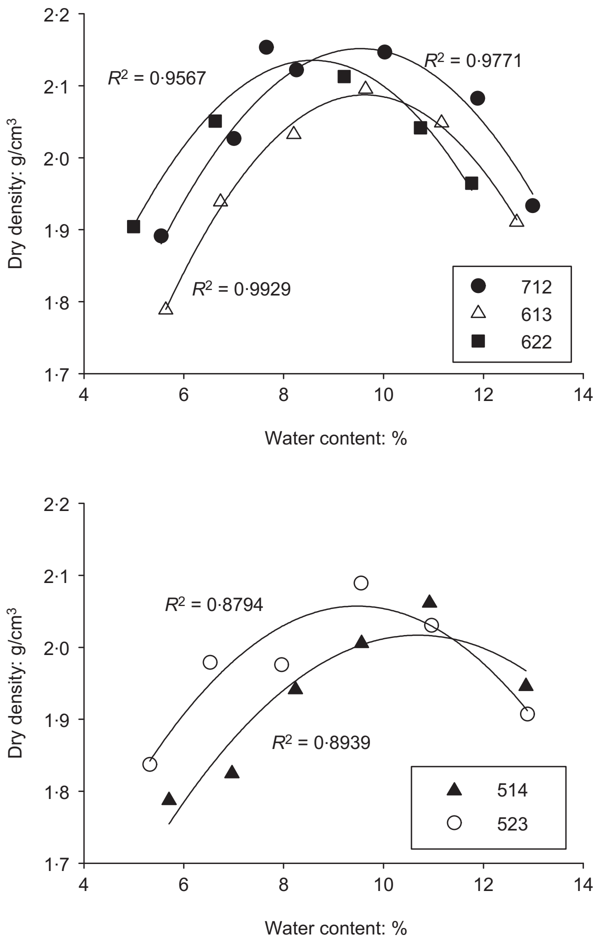

Figure 2. w–ρ_d OSET results, for all RE mixes

3.2 Investigation 2: British Standard test verification

Of the 45 ρ_d–w plots produced using the three BS1377 methods, all 15 of the HMCT, 12 of the LMCT and 14 of the VHT were deemed acceptable to provide a value for w_{opt}. Of the three discounted LMCT plots, the first 514 and 523 results produced no peak within the investigated range of w and the first 613 result showed excessive scatter, with R^2 = 0·769. The first 613 result from the VHT was also discounted owing to excessive scatter, with R^2 = 0·747. The two remaining w_{opt} values obtained for the corresponding method and RE mix were used to calculate the average and range of w_{opt} for the RE determined by the BS1377 procedures. Figure 3 shows examples of the results obtained during one full test of the 613 RE mix, with six ρ_d–w_{opt} points plotted for each of the three methods and a quadratic curve fitted to the values.

When comparing the w_{opt} and ρ_{dmax} results obtained from the BS1377 tests to the OSET results, at least one of the VHT results falls within the limits presented in Table 5 for all of the RE mixes except 613, where one w_{opt} value is greater and the other is smaller than the on-site range. Three RE mixes, 514, 613 and 712, also have at least one of the LMCT results within the OSET range, whereas all of the HMCTs produce results drier and more dense than the OSET. Figure 4 shows the nine values calculated using the three BS1377 methods and the three values calculated using the OSET, for all RE mixes and demonstrates that the VHT results match those obtained in the OSETs.

This result can be easily explained because the w_{opt} and ρ_{dmax} values obtained depend on the compactive effort used during the test. The VHT used the same pneumatic hammer to compact the RE as used in the OSET and, while the OSET compacts only one 150 mm layer of RE rather than three 40 mm layers, both tests result in the ringing noise described by Walker *et al.* (2005). This indicates that the RE is fully compacted, and thus the ρ_{dmax} has been reached; any compactive effort applied after this ringing is heard is likely to be dissipated through the large vibrations of the mould and will not contribute to increasing the ρ_d.

One of the major drawbacks to all three BS1377 methods is that they are designed to calculate the characteristic

RE mix	Optimum water content range: %		Corresponding dry density: g/cm^3	
	Minimum	Maximum	Minimum	Maximum
514	10·40	10·65	2·00	2·01
523	9·46	9·78	2·06	2·04
613	9·60	9·92	2·08	2·11
622	8·40	9·02	2·08	2·13
712	8·76	9·54	2·14	2·15

Table 5. The maximum and minimum w and ρ_d values taken as the range of values considered to be 'at optimum' for on-site compaction for all five RE mixes

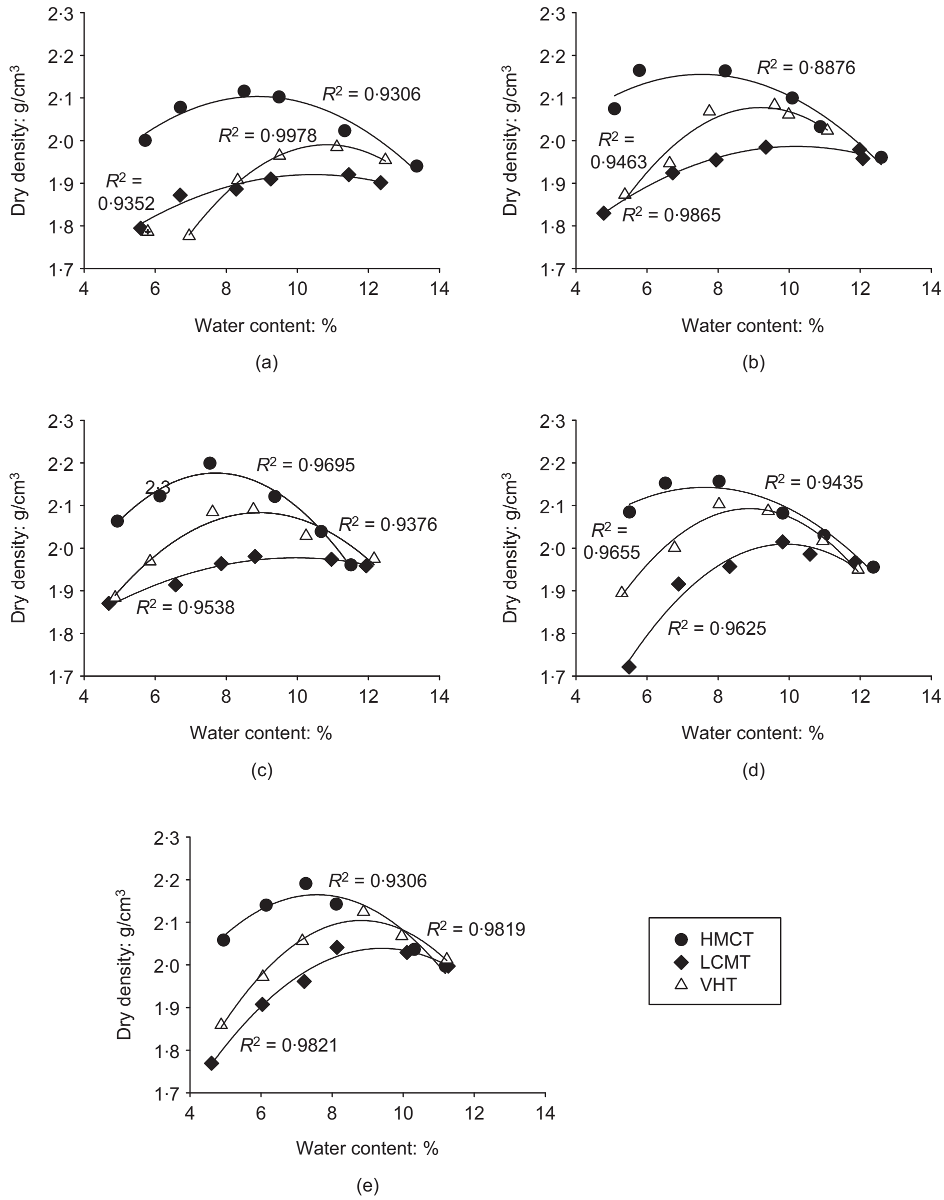

Figure 3. One set of w–ρ_d BS1377 results for all RE mixes: (a) 514; (b) 523; (c) 613; (d) 622; (e) 712

w_{opt}–ρ_{dmax} values for a given geotechnical material, under a given compactive effort, but not to determine whether the material is at its optimum value. This means that performing any of the methods is not an appropriate way of establishing whether or not the pile of RE awaiting compaction on a construction site is at optimum. However, because a number of laboratory tests are required on the RE before construction may begin, it is proposed that the VHT is used to determine the w_{opt} within a laboratory before construction commences and other quantitative methods are developed to determine the water content of a large pile of RE on a construction site.

3.3 Investigation 3: Drop test verification

3.3.1 Investigating the effect of the operator

Figure 5 shows the 50 w_{opt} values returned by the individual operators all performing the WDT. It is clear from these results that the DT lacks repeatability. The range of w deemed to be at optimum was over 2·5% for all the RE mixes except 514, which

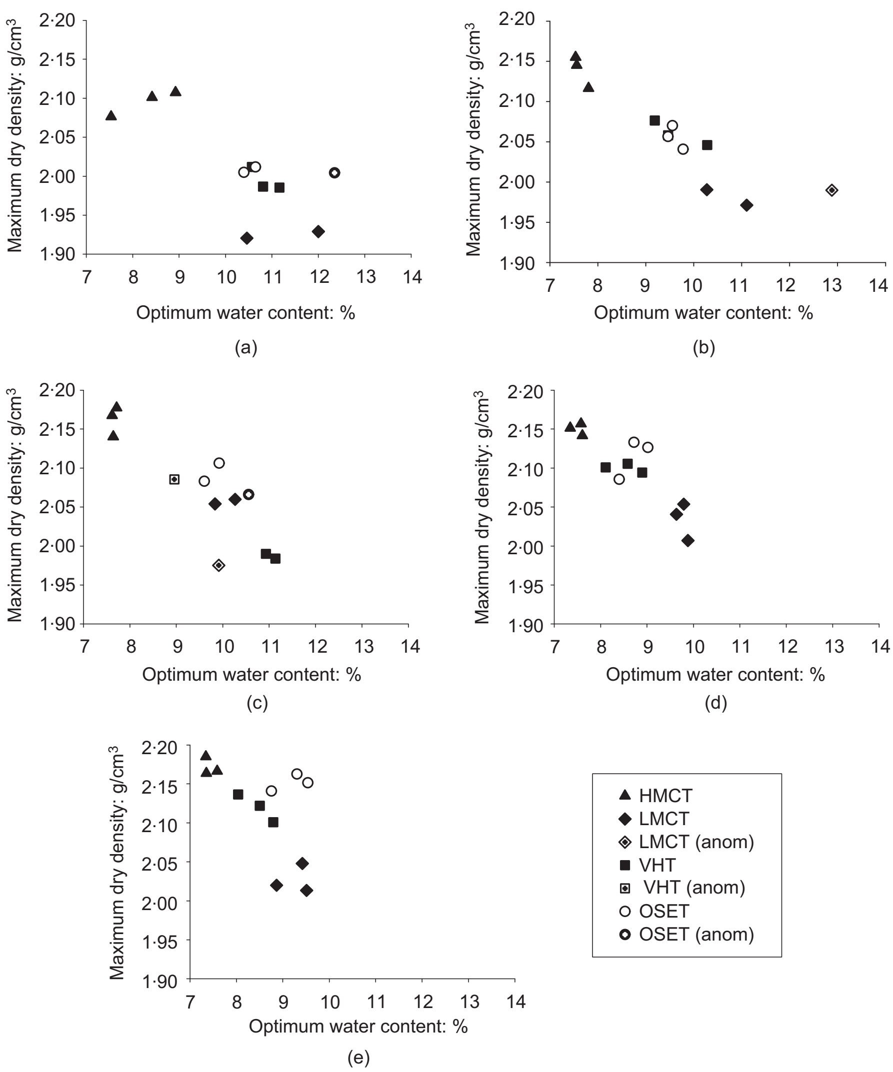

Figure 4. w_{opt}–ρ_{dmax} results for all RE mixes: (a) 514; (b) 523; (c) 613; (d) 622; (e) 712

had a range of 1·8%. This equates to a percentage difference of 15% for the 514 mix and 29% for 523. Figure 6 shows clearly that the range of results is not related to the operator height, since the percentage error of the w_{opt} values returned by the operators has no correlation with the height of the operator. Although no other factors were directly investigated, it is suggested that the amount of operator input during the DT procedure is likely to contribute to the error, particularly for the WDT, which provides no quantitative value of 'a few' to determine whether the sample is at optimum and also leaves the operator to make a judgement on how hard to compact the RE ball in the hand. It is suggested, therefore, that these operator judgements are likely to be the largest contributors to the variability in the w_{opt} values obtained.

3.3.2 Investigating the effect of the RE mix

Since no quantitative value of 'a few' is given in Walker *et al.* (2005) to determine whether the RE is at optimum, the same number of pieces into which the RE ball shatters as stated by Houben and Guillaud (1989), four or five, was used in these tests as the measure to determine if the RE was at optimum. Table 6 shows the four w values for which either of the DTs returned an 'at optimum' result. The table, however, does not show an interesting result, which is that for all four results the other two balls dropped at the same water content did not return 'at optimum' results, but rather verdicts indicating that the RE was either too wet or too dry. Figure 7 shows the 514 results for both DTs, plotting the number of pieces the RE balls broke into and, although a w_{opt} can be seen at 11%, the

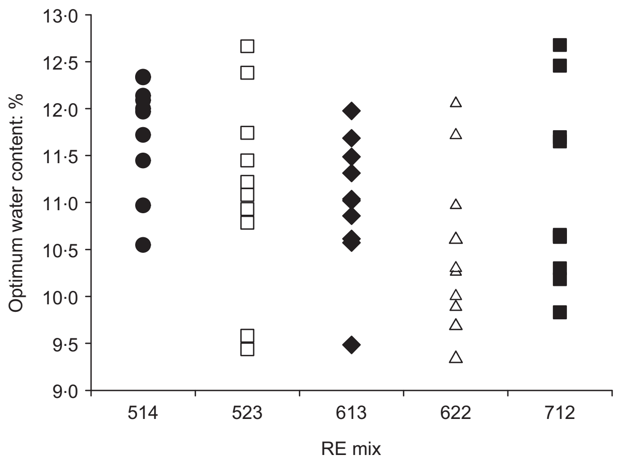

Figure 5. All w_{opt} values returned by 50 operators performing the WDT

RE mix	Water content: %	
	HGDT	WDT
514	10·987	—
523	—	9·209
613	—	—
622	7·484	8·157
712	—	—

Note: The symbol — denotes no sample returned an 'at optimum' result.

Table 6. w values deemed as 'at optimum' using both DT methods for all five RE mixes

other two results using the HGDT for the same w both indicated that the RE was too wet, so the verdict from that set of results could also be interpreted as too wet. This lack of repeatability in the results casts doubts on the effectiveness of the DT, as it would be expected that a robust procedure would return the same verdict for the same RE at the same w, performed by the same operator. No clear differences in the results obtained from the two different DT methods could be seen. This is thought to be due to the similar methods described in the guidelines and the fact that each set of instructions leaves fundamental parts of the test to the discretion of the operator: in the case of HGDT, the size of the ball to be dropped and for WDT, the amount of compression the ball should be put under, and the lack of a quantitative value for 'a few'. This means that both tests are fully reliant on the experience of the operator, not the method itself, to give correct results.

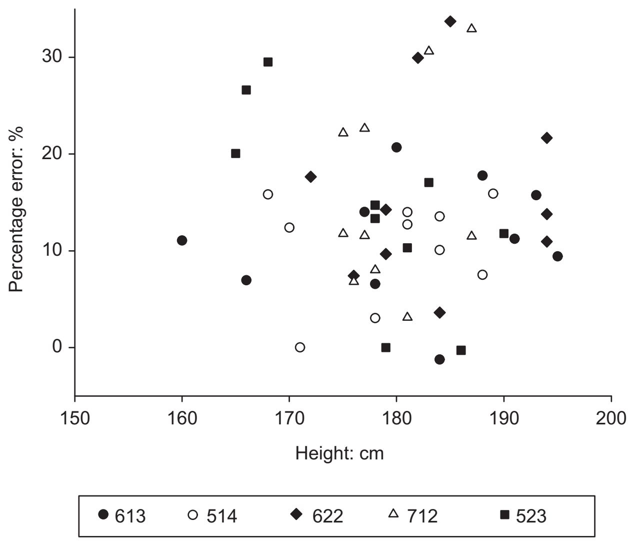

Figure 6. Percentage error plotted against height of the operator for all five RE mixes for the DT. A negative percentage error indicates a w lower than the OSET range for the given RE mix; a positive percentage error indicates a w greater than the OSET range for the given RE mix

The only potential advantage of the DT methods is that they are designed to determine if a RE mix is at optimum or not at optimum. This means that, in theory, the DT can be quickly performed on site to ensure the RE is close to optimum and construction can start with the knowledge that ρ_{dmax} will be achieved. However, none of the 30 samples tested within the OSET w_{opt} range returned an optimum result, and only three samples out of the 318 samples tested within the w_{opt} regions given by any of the three BS1377 methods returned an optimum result. This clearly shows that, in practice, the DT does not indicate an optimum result when the RE is either at or close to its w_{opt} for RE construction. The test is fundamentally flawed, and should not be used as part of RE quality control procedures.

4. Conclusion

The successful establishment of a range of w, by way of the OSET, that could be considered as a set of reference values has enabled the assessment of the existing DT and BS1377 methods to determine the w_{opt} for RE construction. The results presented in Table 5 provide the maximum and minimum values for the five mixes investigated; however, it is important to note that these values need to be considered as appropriate for the given RE mix only when using the same, or very similar, pneumatic hammer methods of compacting walls and should not be used as a universal set of reference data.

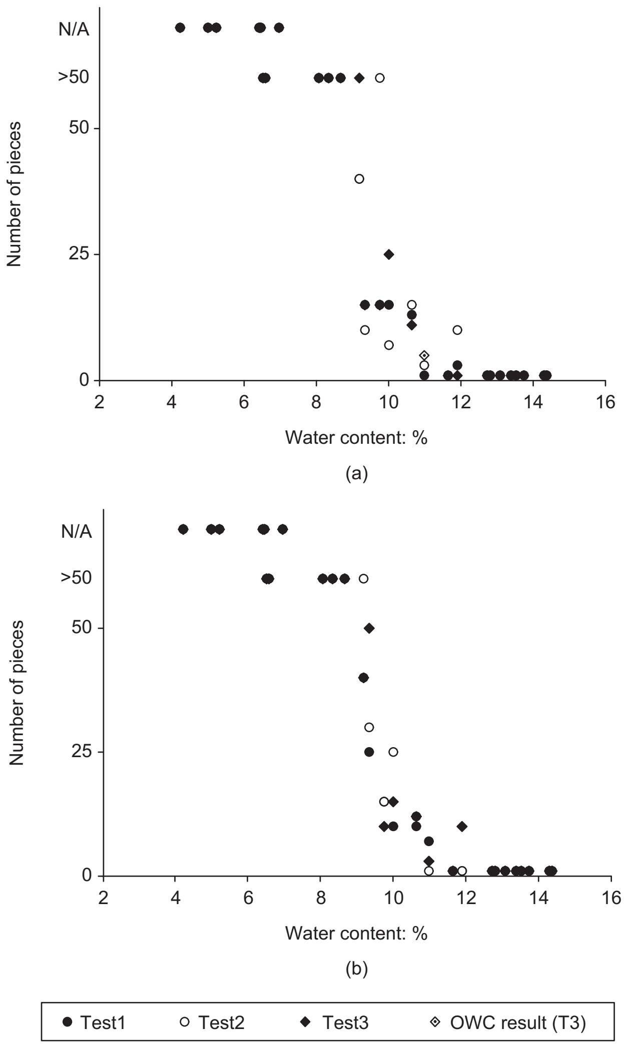

Figure 7. Results produced by (a) HGDT and (b) WDT for the 514 RE mix. The N/A results indicate that the RE was too dry to form into a ball and the test could not be performed

The DT results clearly show that the both the HGDT and WDT are unsuitable for use on site to establish if the RE mix is at optimum. First, the lack of repeatability in the method means that the test cannot be considered as a universal test procedure. The large spread in errors produced by the different operators, accompanied by different verdicts produced by the same operator, shows that the DT method does not produce reliable results that can be repeated by different people in different locations. Second, the accuracy of the results must also be questioned because no DT produced an 'at optimum' verdict for the RE samples tested within the OSET range and only three results returned an 'at optimum' verdict for the RE samples tested within any of the BS1377 test w_{opt} ranges. The aim of the DT is to enable builders to check that the RE is at the correct water content before compaction begins and, with this investigation showing the method lacks both reliability and accuracy, only one recommendation can be made. The DT should not be used within the earth building industry to determine w_{opt}, or as an accepted quality control measure for ensuring adequate compaction of RE walls. There does not seem to be a way of maintaining the simplicity of the DT while ensuring decent accuracy and repeatability, and the test does not seem fit-for-purpose for modern construction.

The investigation into the BS1377 methods clearly shows that the HMCT provides an incorrect measure of a RE wall's w_{opt} and, although both the LMCT and VHT methods provide results within the OSET range, the VHT method provides the most similar results, with w_{opt} values within, or surrounding, the OSET range for all five RE mixes. The use of similar compactive procedures in the OSET and VHT is suggested as the reason for this result and it is proposed that, for all RE construction projects, the RE mix should be subjected to the VHT in a laboratory so that w_{opt} and ρ_{dmax} values can be established before construction commences. It is hoped, with further work, to modify the VHT to be utilised on site, as a measure of the w_{opt} for the RE mix being used in construction, and this would enable the modified VHT to provide an 'at optimum' or 'not at optimum' verdict for the RE during the construction of RE structures.

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