



Specification of pulverised-fuel ash for use as general fill

Prepared for UK Quality Ash Association

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Executive Summary

In the UK, the introduction of a tax on material sent to landfill and the tightening of planning consents for disposal provide powerful incentives for the use of industrial by-products. Pulverised-fuel ash (known as fly ash in many parts of the world) is just such an industrial by-product. It has a long history of successful use as general fill including use in environmentally sensitive locations. However, the current Series 600, Specification for Highway Works and associated Notes for Guidance (MCHW 1 and 2) treat pulverised-fuel ash as a manufactured material and apply an end product specification for compaction. The United Kingdom Quality Ash Association commission the University of Newcastle and TRL Limited to review MCHW 1 and MCHW 2 with respect to pulverised-fuel ash general fill.

The specification for pulverised-fuel ash also requires that the maximum dry density and optimum moisture content are determined for each consignment of pulverised-fuel ash delivered to site: a process that can take up to two days. A method specification is more commonly applied to natural fill materials used as general fill and since pulverised-fuel ash is a particulate material, like natural soil, there is no reason that a method specification could not be used for pulverised-fuel ash as a general fill. Further, there is significant historical evidence that method specifications have successfully been used to control compaction leading to pulverised-fuel ash fills that have remained in place for over forty years. The introduction of a method-based specification for the use of pulverised-fuel ash as general fill would enable its greater use and thus reduce the UK-wide need for landfill.

In addition, the specification requires testing to determine effective shear strength parameters under fully saturated conditions for embankment design. No guidance on whether peak or post-peak parameters are to be selected for design purposes or, indeed, on appropriate factors of safety is given. As a result most engineers test pulverised-fuel ash in the fully saturated condition, select post-peak effective shear strength parameters for design and apply a conservative factor of safety. As the testing protocol represents a worst case scenario the application of such a conservative approach can be questioned.

The background to the need for increased use of pulverised-fuel ash in the construction of general fill is described. The history and development of the Specification are also outlined. The current Specification, and associated documents, are described in some detail. From this the case for a new approach to the specification of pulverised-fuel ash is made. The new approach is set within the context of the current Specification for Highway Works and associated Notes for Guidance (MCHW 1 and 2), such that it can be simply and rapidly incorporated into these documents. The new approach is thus proposed as changes to MCHW 1 and 2 to encourage the greater use of pulverised-fuel ash in general fill, whilst ensuring the continued construction of stable earthwork structures. Guidance on the use of pulverised-fuel ash in earthworks is also given.

In this document pulverised-fuel ash for use as general fill is treated as a granular material. This is in contrast to the current Specification (MCHW 1 and 2), which treats pulverised-fuel ash as a cohesive material. Accordingly there is a need to amend other elements of the Specification (i.e., Classes 7B, 7G and 9C selected fill) to reflect this change.

1 Introduction

Pulverised-fuel ash (known as fly ash in many parts of the world) is an industrial by-product with a long history of successful use as general fill, including use in environmentally sensitive locations. The current economic and political climate provides a strong incentive for the greater use of industrial by-products in construction. This may lead to both reduced costs and environmental benefits - such as energy saving, a reduction in the use of natural resources and in the need for lagoon and landfill sites to store by-products.

Over the last few years Government policy, backed by regulation, legislation and international agreements, has tended towards taking greater account of environmental issues. Not least among the considerations addressed by such policy changes has been the introduction of a tax on material sent to landfill. The landfill tax has created an economic incentive for the use of industrial by-products in construction and other industries. Other 'green' taxes include the energy tax, introduced in 1999, and the aggregate levy, which will be introduced from 1 April 2002. Further incentives have been applied by tightening planning constraints on industrial by-product disposal sites.

While Government policy is helping to improve environmental awareness, clients are also seeking a greener product because of the perceived direct economic and, less tangible, image benefits. A consequence of this approach is that materials once viewed as waste products are routinely being considered for use or recovery. Thus, they can be used in environmentally sensitive locations provided due care is taken.

While there are benefits to moving towards a more sustainable approach, the construction industry is hampered by a number of factors, including specifications. Many of the current construction specifications will thus require modification in order fully to reflect recent policy changes in respect of the use of industrial by-products. Pulverised-fuel ash, which is abstracted from the flue gases of coal fired power stations, is such a by-product. It is used in the construction industry as, for example, a concrete addition and as fill.

Pulverised-fuel ash was used both extensively and successfully as both selected and general fill from the 1940s onwards. However, since the introduction of an end product specification for highway works in 1986 the amount of pulverised-fuel ash used for such purposes has decreased.

In order to address this situation, the United Kingdom Quality Ash Association commissioned the University of Newcastle and TRL Limited to review the current Specification for Highway Works (MCHW 1 and 2) in relation to the use of pulverised-fuel ash as general fill earthworks and to propose amendments. This report presents the results of this work.

It proposes additions, deletions and replacements to the existing documents to bring the treatment of pulverised-fuel ash into line with that of similarly variable natural soils. The detailed case for the changes to the Specification is made by Winter and Clarke (*In press*) and is further substantiated in this report, which also includes guidance on the use of pulverised-fuel ash as general fill.

2 Pulverised-fuel ash

Pulverised-fuel ash is a by-product from the production of energy from coal-fired power stations. This material is known as fly ash in many parts of the world. There are two forms of ash, furnace bottom ash and pulverised-fuel ash. The former is a clinker left in the bottom of the furnace, while the latter is collected from the exhaust gases using the process of electrostatic precipitation.

The quantity of ash produced as a by-product of burning coal to produce electricity in the UK is significant. The United Kingdom Quality Ash Association estimated production for 1997 at around 6 million tonnes for pulverised-fuel ash and 1.3 million tonnes for furnace bottom ash. Longannet power station in Fife, for example, is capable of producing a maximum of 4,350 tonnes of pulverised-fuel ash per day.

Whitbread *et al.* (1991) estimated that more than 4,000 hectares were utilised as pulverised-fuel ash disposal sites in England and Wales (figures were not available for Scotland). One disposal site is expected to reach a maximum height of 36.6m and cover 160 hectares by the time it is completed in 2006, at an estimated construction cost of more than £30M (Anon, 1997).

By far the bulk of the furnace bottom ash material produced is sold for reuse. Around 3M tonnes per annum of pulverised-fuel ash is utilised in applications ranging from cement and structural elements to use as general fill. However, around 3M tonnes of pulverised-fuel ash remains unsold. This corresponds to around 2Mm³ of compacted fill for a material with a typical maximum dry density up to 1.5Mg/m³.

There is an increasing acceptance of the basic concept that for by-products that are produced in large quantities, such as pulverised-fuel ash, a balance of high utility, intermediate utility and low utility applications is required (Winter and Henderson, 2001). This enables the residual quantities left unused to be minimised, the economic returns from the sale of the material to be maximised and the cost of disposal minimised. At present the bulk of pulverised-fuel ash sales are for utilisation in cement and structural element manufacture at the high utility end of the scale. Estimates indicate that in Scotland, for example, less than 30% of pulverised-fuel ash is sold for reuse and that of that sold between 30% and 40% is for use as low utility general fill. In the UK the figures for pulverised-fuel ash sales are estimated to be around 50%. Nonetheless, the potential for the increased use of pulverised-fuel ash in place of natural fills is significant.

In addition to the space required to store pulverised-fuel ash, there are also external cost pressures placed on the power station operators to use their pulverised-fuel ash by-product. Disposal in lagoons and other forms of disposal are subject to landfill tax. The tax for inactive waste, which applies to pulverised-fuel ash, has been maintained at £2 per tonne. However, the tax for active waste the tax was increased from its original level of £7/tonne to £10/tonne in April 1999, to £11/tonne in April 2000 and to £12/tonne in April 2001. Subsequent rises of £1/tonne per annum will be implemented in April of each year until 2004, when the

active waste rate will be £15/tonne. In addition, planning authorities can, and do, set targets for the use of pulverised-fuel ash as part of the conditions for granting or renewing planning permission for the use of disposal lagoons (Figure 1). This includes the use of pulverised-fuel ash as general fill. The Government provided further incentive to the use of secondary aggregates in place of primary materials with the announcement of a tax of £1.60/tonne on primary aggregates in the Chancellor of the Exchequer's March 2000 budget speech.

There remains a view, however, that the use of pulverised-fuel ash for earthworks is limited by the lack of information on the properties of pulverised-fuel ash from the various sources. Pulverised-fuel ash is inherently variable, both between sources (Figure 2) and on a day-to-day basis from a single source (Figure 3). The data in Figure 2 also indicates that, as sources of coal have changed, so has the variability of the pulverised-fuel ash produced increased, albeit to a relatively small extent. This can significantly affect the minimum level of compaction required and as a result an end product has been deemed appropriate, rather than the simpler and less costly method specification applied to conventional natural fills. There is also evidence that the variability of pulverised-fuel ash has led to problems in establishing and attaining end product dry density requirements, with resulting contractual problems, and loss of economy to the end-user.

Historically, however, in excess of 30M tonnes of pulverised-fuel ash has been used successfully for structural and general fills for over forty years on projects such as the Dewsbury earth retaining wall (Jones *et al.*, 1990), road embankments at the A308 Staines by-pass (Margason and Cross, 1966) and Durham Road by-pass at Stockton-on-Tees. The construction of fills has been based on highway specifications that have evolved from research, practice, policy and previous specifications.

It is clear that satisfactory earthworks structures can be formed from pulverised-fuel ash and experience in both

the highway construction field and in the construction of pulverised-fuel ash disposal lagoon dams (Figure 4) provides confirmation. It is also clear that the industry uses the Specification for Highway Works as the standard for most engineered fill (Treuter and Charles, 1996), from infrastructure works to golf courses.

3 History of the specification

The current compaction specification (MCHW 1) treats pulverised-fuel ash as a manufactured material and requires an end product in terms of a percentage of the maximum dry density. This approach was first implemented in the 1986 Specification for Highway Works (SHW, 1986).

Prior to 1986 the 1976 and 1969 Specifications for Road and Bridge Works (SRBW, 1969; 1976) included pulverised-fuel ash within the definition of 'uniformly-graded material' (see also Sherwood, 1975), itself subject to a method specification for compaction. A range between optimum moisture content and optimum plus 1.5% was given as a starting point for the consideration of suitability limits.

Earlier specifications (e.g., SRBW, 1963) utilised an end product specification for compaction based upon a maximum permissible air content. The specification was applied to all fills, including, by implication, pulverised-fuel ash.

Natural soils, themselves potentially highly variable, were treated by method compaction by all Specifications after SRBW (1963).

4 Current specification

4.1 General requirements

The current Specification (MCHW 1 and 2) defines pulverised-fuel ash as 'solid material extracted by



Figure 1 A typical pulverised-fuel ash disposal lagoon at the time of excavation

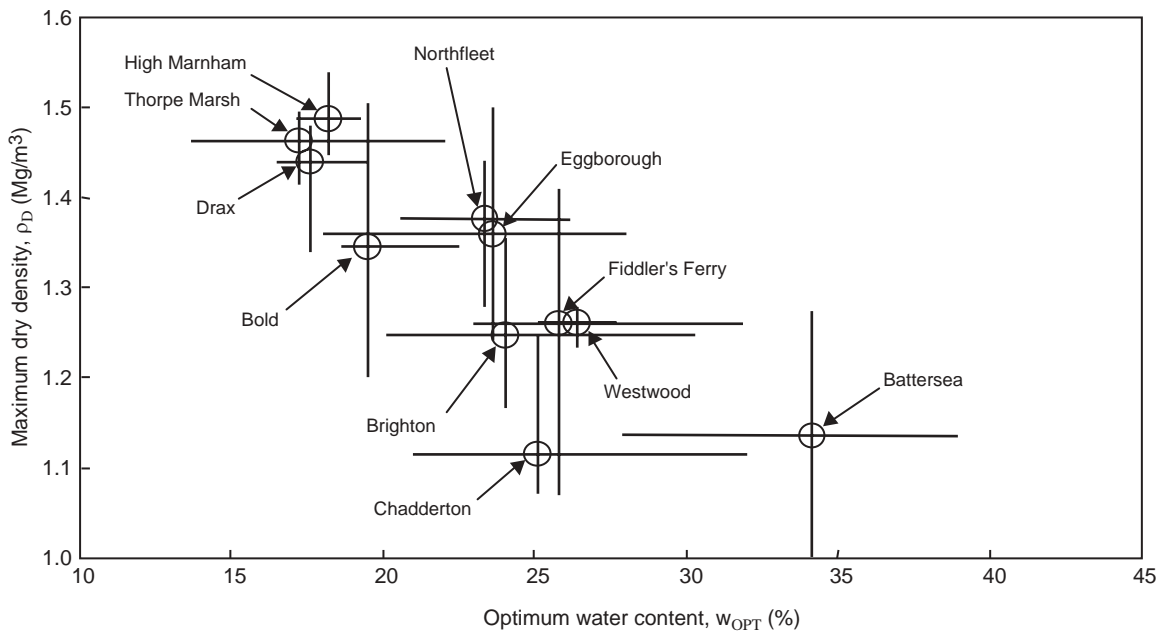


Figure 2 Variation of maximum dry density and optimum moisture content of pulverised-fuel ash from several sources over a period of time

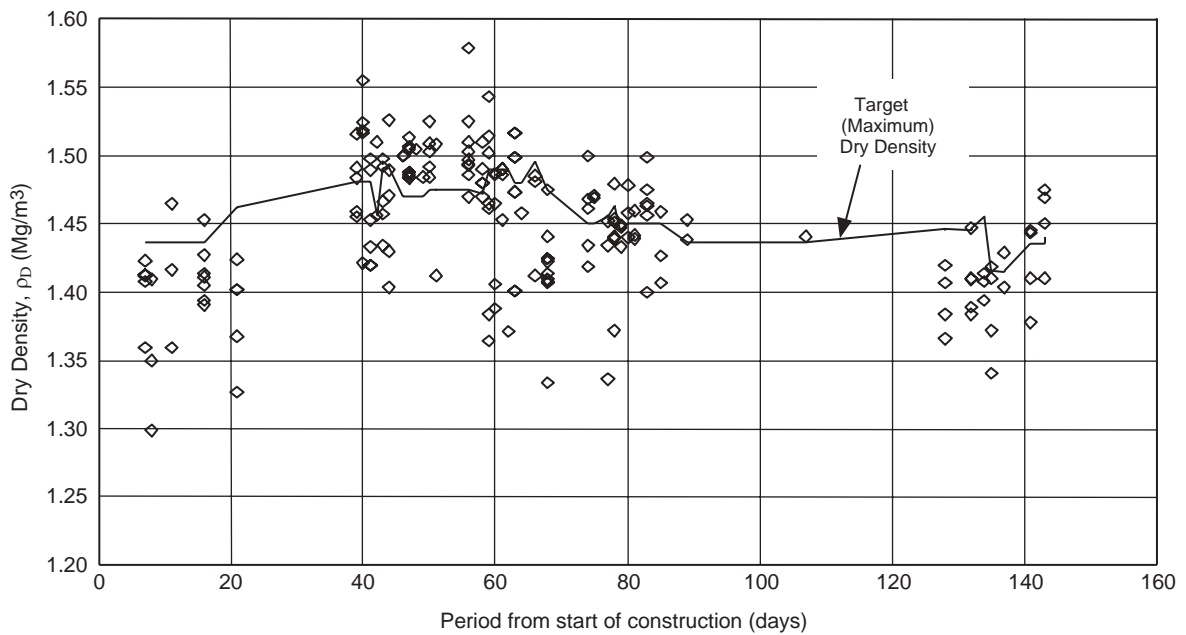


Figure 3 Variation in dry density and associated target (maximum) dry densities with time for one site



Figure 4 Construction of a pulverised-fuel ash disposal lagoon dam

electrostatic and mechanical means from the flue gases of furnaces fired with pulverised bituminous coal' with a maximum particle size of 3mm (Clause 601.7). Pulverised-fuel ash is generally a silt-sized material as shown in Figures 5 and 6. The classes of pulverised-fuel ash found in Table 6/1 (see Table 1) of the Specification vary according to whether the material is conditioned or obtained from lagoons or stockpiles (DMRB 4.1.1: Clauses 5.62 to 5.65). Class 2E (pulverised-fuel ash as general fill) includes lagoon pulverised-fuel ash, that is material that has been transported in slurry form and stored in lagoons, which may be used as general fill. Such material may contain furnace bottom ash and may be subject to some segregation of sizes during filling of the lagoon. Because of this lagoon pulverised-fuel ash may be more variable than stockpiled pulverised-fuel ash, which is also included as a Class 2E material. Once stockpiled it tends to approach its optimum moisture content after a period of storage.

Conditioned pulverised-fuel ash can be used as higher quality selected fill: either as fill to structures and reinforced earth (Class 7B) or for stabilisation with cements to form capping (Class 7G/9C). It is collected directly from the flue gases created by the coal burning process in hoppers. Sufficient water is added to bring it to a state suitable for compaction. The DMRB 4.1.1 (Clause 5.63) states that the optimum moisture content of conditioned pulverised-fuel ash is typically 25%, but may be as high as 35%. However, in reality the optimum moisture content may be in excess of this value. Data from Scotland indicates that the optimum moisture content of conditioned ash may be as low as 18% while that of lagoon ash may be as high as 28%. Historically, pulverised-fuel ash was considered a lightweight fill but there are a few instances when the density is such that it is nearer to that of some natural soils. Published data show that the optimum moisture content can vary from 17% to 34% and the maximum dry density from 1.1Mg/m^3 to 1.5Mg/m^3

(Figure 2), but it is possible for the maximum dry density to lie outwith this range.

Variations for single sources are generally greater than in the past, a factor that is emphasised by base-loading in the winter and double-shifting in the summer. Typical maximum dry density ranges for a pulverised-fuel ash from a base-loading regime might be in the range 1.37Mg/m^3 to 1.47Mg/m^3 , while that for double-shifting is more likely to be between 1.17Mg/m^3 and 1.32Mg/m^3 . However, the range can be greater when sources within England and Wales are compared: potentially between 0.87Mg/m^3 and 1.47Mg/m^3 , with optimum moisture content varying between 17% and 46%. Although conditioned ash direct from the hopper can be used, reclaimed (lagooned or stockpiled) ash is generally more suitable for use as fill. This is because the moisture content tends to reach equilibrium close to optimum and also because there are greater volumes available for supply on a daily basis. Furthermore, most water-soluble material has been washed out of lagoon pulverised-fuel ash and it can therefore be more suitable for use in some situations than fresh conditioned or stockpiled material. The DMRB 4.1.1 (Clause 4.1) states that the main objective of acceptability assessment is to 'enable the scheme to be constructed to a satisfactory standard of design and longevity for the minimum cost'. In order for this to occur acceptability criteria and limits must be set to ensure that the required compaction can be achieved. The DMRB (Clause 5.66) goes on to note that for general fill purposes, it is sufficient to rely on the end product specification therefore bulk density limits need not be stated. However, this is clearly dependent upon the nature of the design and whether the weight of the fill is critical to the design. In such cases, bulk density limits must be stated along with the end product. These values may be typically between 1.3Mg/m^3 and 1.65Mg/m^3 for lagoon, stockpiled or conditioned. Data from Scotland indicates that maximum dry densities might

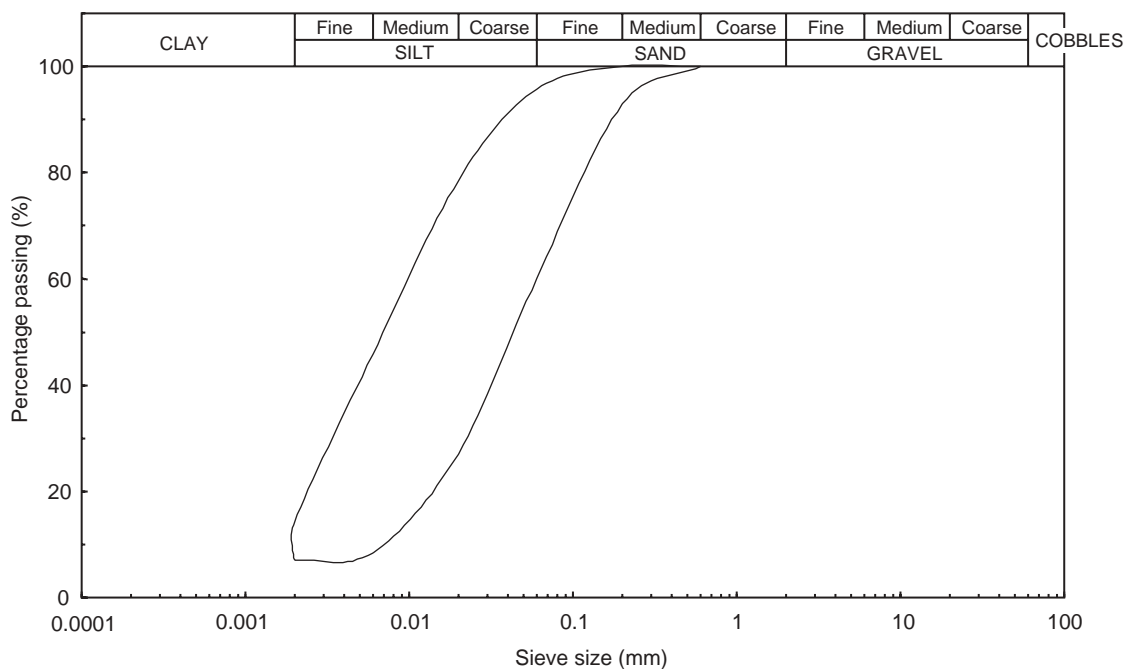


Figure 5 Typical range of particle size distributions of pulverised-fuel ash. Data from authors' files from a number of power stations



Figure 6 Pulverised-fuel ash, a 23mm diameter one-pound coin is shown for scale. (The larger *lumps* are agglomerations of small particles)

Table 1 Classes of pulverised-fuel ash within the Specification for Highway Works (MCHW 1)

<i>Class</i>	<i>Description</i>	<i>Use</i>	<i>Permitted constituents</i>	<i>Acceptability determination</i>	<i>Compaction requirements</i>
2E	Reclaimed pulverised-fuel ash cohesive material.	General fill.	Reclaimed material from lagoon or stockpile containing not more than 20% furnace bottom ash.	Moisture content or bulk density.	End product 95% of maximum dry density of BS 1377: Part 4 (2.5kg rammer method).
7B	Selected conditioned pulverised-fuel ash cohesive material.	Fill to structures and reinforced earth.	Conditioned material direct from power station dust collection system and to which a controlled quantity of water has been added.	Moisture content, bulk density and other requirements depending on use.	End product 95% of maximum dry density of BS 1377: Part 4 (2.5kg rammer method).
7G	Selected conditioned pulverised-fuel ash cohesive material.	For stabilisation with cement to form capping (Class 9C).	Conditioned material direct from power station dust collection system and to which a controlled quantity of water has been added.	Moisture content and total sulphate.	Not applicable.
9C	Cement stabilised conditioned pulverised-fuel ash cohesive material.	Capping.	Class 7G with addition of cement according to Clause 614.	Pulverisation, bearing ratio or moisture content.	End product 95% of maximum dry density of BS 1377: Part 4 (2.5kg rammer method).

be in the region of 1.12Mg/m³ and 1.25Mg/m³ for lagoon and conditioned pulverised-fuel ash respectively: those for sources in England and Wales are given above .

The DMRB 4.1.1 quite correctly points out that, prior to specifying the use of pulverised-fuel ash, especially if its use is required to satisfy a design which relies on lightweight fill, it is advisable to check on the sources and likely availability with the appropriate company. They should also be able to provide typical test results for the various sources but note that pulverised-fuel ash, especially conditioned pulverised-fuel ash, can vary such that the typical results may not represent the properties of the fill at the time of use.

Some care is required in interpreting the results of compaction tests on pulverised-fuel ash. Typically air voids will be in the region of 8% to 15% for an adequately compacted fill. This is somewhat higher than is usually required for a natural soil, due to the nature of the particle size distribution. It suggests there is potential for subsequent water ingress and collapse on inundation though, in practice, this may not be an issue since the maximum dry density restricts further volume changes. Further, the air voids of some pulverised-fuel ash will be filled as a result of pozzolanic reactions, creating an inherently more stable material. The effects of ageing on pulverised-fuel ash are discussed in Section 4.2.

Eurocode 7 (1997) currently has ENV status. However, it is anticipated that it will have full EN (mandatory) status during the lifetime of this report and is thus treated as such herein. Eurocode 7 specifically refers to pulverised-fuel ash as a suitable fill material. Further, it lists aspects that must be considered when choosing fill. This includes compactibility and cementation, both of which are key factors in the use of pulverised-fuel ash. Eurocode 7 covers

design rather than construction but design is an essential part of the construction process.

4.2 Design parameters for pulverised-fuel ash earthworks

The current Specification only covers effective strength parameters of selected fills. However, in good practice the specified tests are carried out for general fill because no alternatives are given. There are alternative tests but because of the experience gained from using parameters derived from the specified tests, it is prudent to continue to use such tests when specifying pulverised-fuel ash as general fill. This helps ensure that unaccustomed practice does not act to the detriment of the increased use of pulverised-fuel ash.

The current Specification is a ‘catch-all’; it thus covers the worst possible case. If a design engineer follows the Specification then the completed project should be safe but may not be the most economic version. Taking a more realistic approach, and using the available knowledge and understanding of pulverised-fuel ash, it should be possible to produce designs that are both safe and economic based on a case lying between the worst possible and most credible cases. This is the approach proposed by Eurocode 7. This may create a problem for the design engineer. Although failure is still highly unlikely the probability of an adverse event is increased. Some conservative design organisations have, in the past, taken the view that exposing their professional indemnity insurance to such increased risks, however slight, is not desirable for their business.

A second issue concerns the selection of design parameters. These can be obtained from trade literature, research publications, suppliers’ databases and a targeted testing programme.

Trade literature is based on historical, average data which can be used for feasibility and preliminary design studies. However, it would be unusual to produce the final design for earthworks on 'average' or historical data of soil and, since pulverised-fuel ash is a particulate material similar to soil, then the same design methodology should apply. Thus, design parameters should be derived from tests on the actual fill to be used.

Data from both research publications and from trade literature, may be site specific. However, the data from research publications is likely to be more detailed. They provide a useful reference, indicate likely performance and highlight relevant issues for the designer. For example, Clarke *et al.* (1993) discuss the effect of time on effective strength parameters for a stockpiled and a conditioned pulverised-fuel ash. The data could be used in a design provided the same source of pulverised-fuel ash will be used in the construction. Research papers do, additionally, make the design engineer aware of the issues and how they could be addressed.

Suppliers' databases are a useful source of information and, with increasing awareness of the need to supply quality data, suppliers have started testing programmes to produce design parameters. This information will be useful at the feasibility stage and, in some cases, the design stage. Tests are often carried out on conditioned ash, which may go to stockpile. Thus, the test data may not represent the future source material. Further, not all suppliers can provide the information. Nor are any of them likely to be able to supply information on existing stockpiled or lagoon ash. This latter source of material is particularly important because of the greater quantities involved and the fact that the supply is more immediately stable than conditioned ash.

In essence, there are two ways to select design parameters. The first is to take published, typical values; the second is to test a specific source of material. The former, used in conjunction with the Specification, will produce a safe design but not necessarily the most economic. Design engineers should normally use parameters measured in a testing programme on the source material. This approach should result in more economic designs, especially if the most credible case is considered, though at the cost of carrying out tests at the start of a project. This approach is the same as that used for natural fills.

Eurocode 7 suggests that a visual examination of pulverised-fuel ash may be sufficient if the project only includes small (<2m) excavations and/or simple (two-storey houses) buildings; that is no further testing is required. Thus, based on Eurocode recommendations, it may be appropriate to use published values for general fill for low-rise structures and projects associated with similar levels of risk. Tests on source materials would be required for all other projects. The latter allows an engineered solution to be produced that is both safe and economic. This approach also fits with the Specification, but there are some reservations.

Effective shear strength parameters for embankment design are taken from tests on fully saturated pulverised-fuel ash compacted to $92\% \pm 2\%$ of maximum dry density (MCHW 1: Clause 636). The test procedure produces a

shear stress-displacement curve. It is assumed that the pulverised-fuel ash is compacted at the optimum moisture content. If that is the case, then the pulverised-fuel ash will exhibit dilatant behaviour due to the degree of compaction, with peak and post-peak shear strengths. These terms are defined in Figure 7. With time, in some ashes, these strengths will increase due to cementation effects. No guidance is given on whether peak or post-peak parameters are to be selected for design purposes. Many engineers select post-peak shear stress values to determine the effective strength parameters. In current practice a global factor of safety of 1.3 is applied to the design of slopes and 3 to foundation designs. Thus, a worst case scenario, the fully saturated post-peak condition, is chosen and a conservative factor of safety selected. Since the worst case scenario is selected, then the use of conservative factors of safety may be questioned since this will lead to excessively safe designs that are uneconomic.

Eurocode 7 uses partial factors of 1.25 for $\tan(\phi')$ and 1.6 for c' . The characteristic values of ϕ' and c' are a cautious estimate of the values affecting the occurrence of the limit state. No guidance is given as to whether peak or post-peak values should be used. Eurocode does, however, allow other factors to be taken into account. The most important of these, with respect to pulverised-fuel ash, are time effects and brittleness. Many ashes increase in strength with time (Raymond, 1961; Clarke *et al.*, 1993). The strength gain can be significant. For example, Tri Utomo and Clarke (1993) have shown a 100% increase in compressive strength over a 28 day period for conditioned ash from Tilbury. This increase in strength is also accompanied by an increase in brittleness. For this reason, it may not be prudent, or indeed safe, to use the peak strength. The post-peak strength, however, also increases in strength with time. Figure 8 shows the envelope of the change in effective strength parameters with time for a typical self-hardening ash.

Therefore, using the principles and guidelines given in Eurocode 7, it would seem appropriate to select a post-peak strength of a fully-saturated material as the characteristic value, but to base that strength on tests carried out sometime after compaction. Yang *et al.* (1993) have shown that 90% of the increase in strength occurs within 28 days of compaction for those ashes that exhibit pozzolanic action.

If these principles are applied to designs based on global factors of safety then it should be possible to reduce the factor of safety since a cautious view is taken of the effective strength parameters. However, the general trend in geotechnical engineering, and other branches of the civil engineering profession, is towards designing on the basis of partial factors as exemplified by Eurocode 7 above.

While Eurocode 7 and other general design guidelines do not specifically recommend upper limits to values of strength, BS8006 does. It states that the upper limit for effective cohesion is 5 kPa. This may be prudent given the brittle nature of pulverised-fuel ash since the cohesion is developed through pozzolanic action.

Note that tests on partially saturated pulverised-fuel ash at the optimum moisture content also show peak and post-

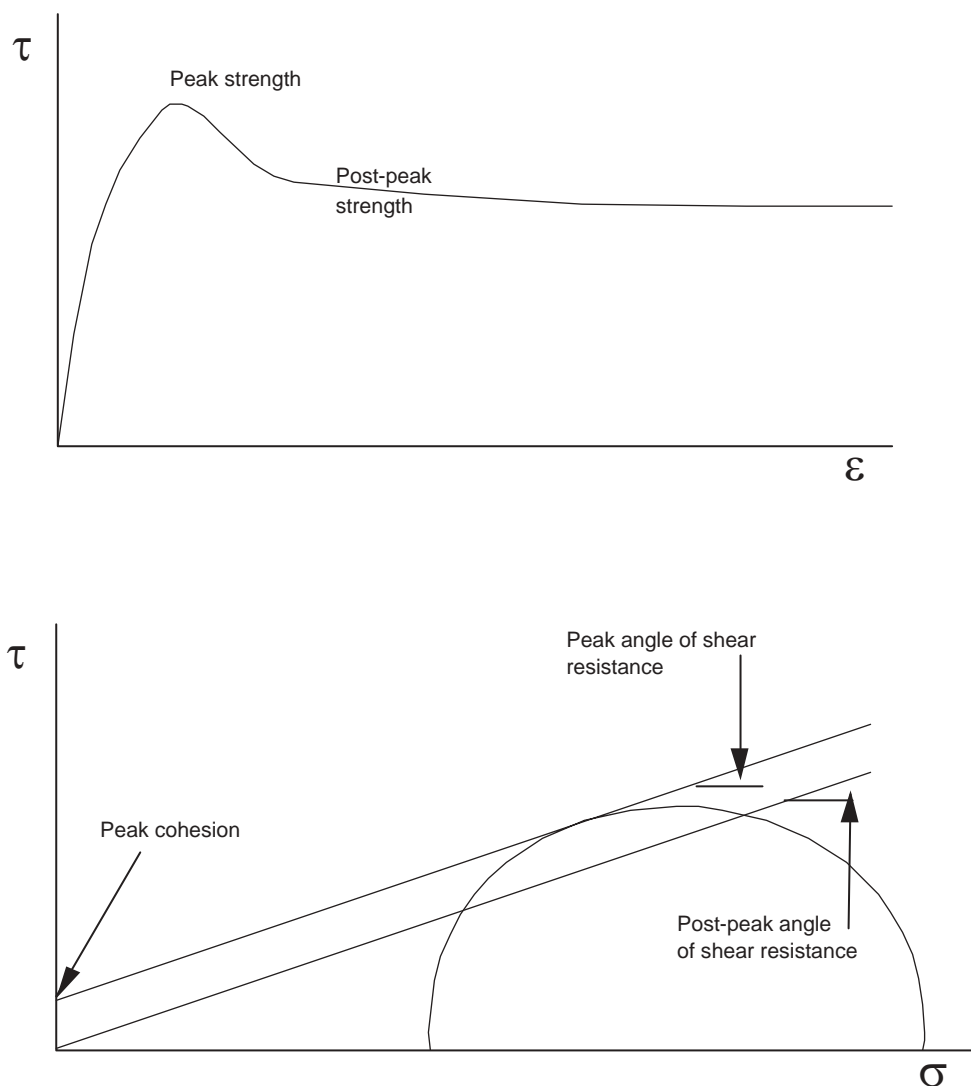


Figure 7 Definition of terms in relation to strength, as used in the text of the report

peak behaviour. In this case, some of the strength may be due to the effects of suction. This suction could dissipate leading to a loss of strength: i.e., tests should normally be carried out on saturated pulverised-fuel ash and the strength of partially saturated pulverised-fuel ash must be treated with caution.

4.3 Compaction of pulverised-fuel ash as general fill

Pulverised-fuel ash is treated as a manufactured product rather than as a waste product or industrial by-product. This is justified in the DMRB by the fact that pulverised-fuel ash properties vary, not only from source to source, but also within a single source. The Contractor is required to supply to the Engineer the following information for each consignment (MCHW 1: Clause 601.18):

- A record of the type and source of the material and the name of the power station from which it was obtained.
- A certificate of results of tests showing that the material complies with the requirements of the compaction specification given in Table 6/1 of the Specification.

Thus, the Specification requires that the British Standard 2.5kg rammer method compaction curve (BS1377: Part 4) is determined for each consignment of pulverised-fuel ash delivered to site. In practice a consignment is not taken as a single lorry load and the rate of testing will be adjusted dependent upon the perceived variability of the pulverised-fuel ash. A minimum target dry density is then set at 95% of the maximum. The results from such a test are likely to be available a minimum of two days after sampling.

Clearly, three possible situations exist, as follows:

- Material can be delivered to site and placed and compacted on the basis of existing limits, that is limits established from earlier consignments. Figure 3 shows the variation in maximum dry density for one site together with the target densities. It shows that pulverised-fuel ash is variable and that it is inappropriate to use target densities from different consignments as an exact control. Despite the difference between the target densities and those achieved, the earthworks were accepted and have not shown any kind of degradation or distress since construction several years ago.

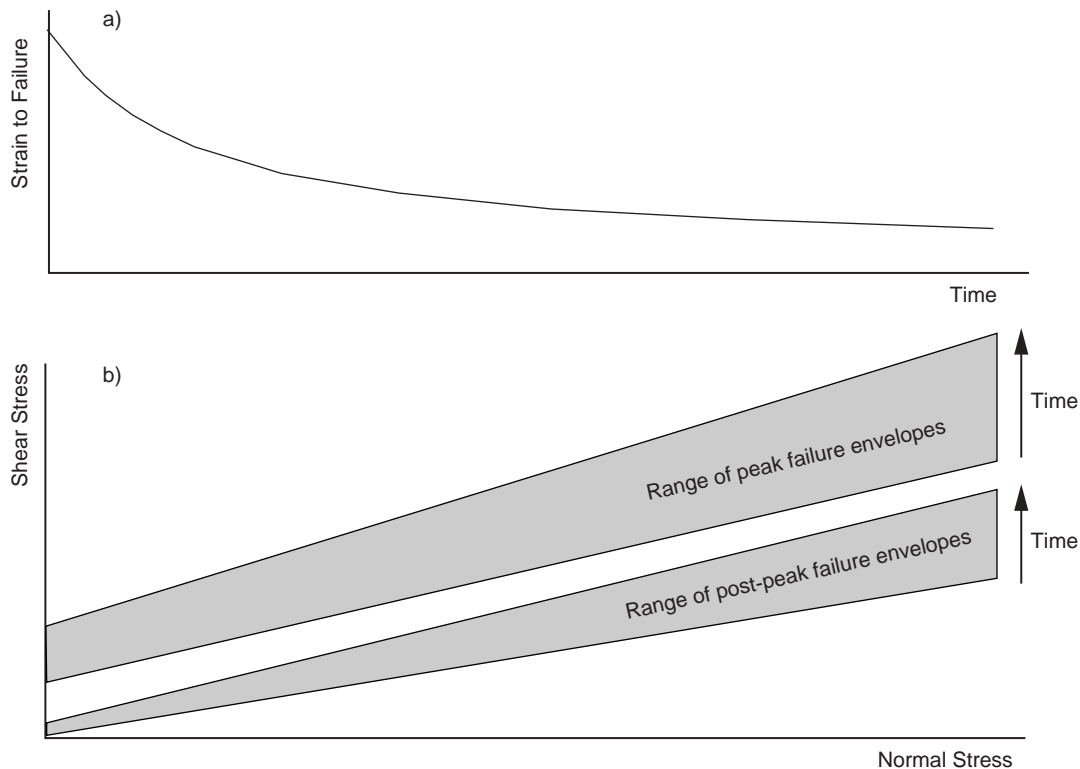


Figure 8 Increase in strength of stockpiled ash with time, showing the changes in (a) brittleness and (b) peak and post-peak strength (after Clarke and Coombs, 1996)

- An average value may be taken from a number of consignments or from tests at source assuming that there is little variation in the target density. This suffers from the same problems as illustrated by the example given in Figure 3.
- Alternatively, each consignment could be stockpiled to await the test results before being placed and compacted. This results in double handling and delay. Further, the moisture content could change due to the ambient temperature and humidity. This is a concern especially when the pulverised-fuel ash has been prepared by adding water at source.

There are disadvantages to all three controls but the compacted material performs as designed even when the difference between the target density and density achieved fall outside the specification. This suggests that the end product control may be relaxed.

The ability to achieve the required compaction may be affected if it is based on the incorrect target density. This is, of course, particularly critical where pulverised-fuel ash is being placed adjacent to structures and where the density achieved may affect the design criteria. Under the requirements of MCHW 1 the Engineer can keep a record of the sources of a manufactured material, and the onus is placed on the Contractor to provide the requisite data including the natural moisture content, the optimum moisture content and the maximum dry density of each consignment. In order to reduce claims and rejection, the Contractor should provide target densities for every consignment if higher quality end product is required. However, while each of these points may be appropriate

for critical selected fill applications, each is also less critical for general fill applications when bulk density limits do not form part of the design requirements.

If a source of pulverised-fuel ash was likened to natural soil from a borrow pit or earthworks excavation then Clarke and Coombs (1996) claim that the variation in properties could be accepted and a method specification could be used. Indeed, other industrial by-products such as burnt and unburnt colliery spoil and spent oil shale, which may be equally variable, are compacted according to a method specification (Winter, 1998). Figure 9 confirms this view. The in-situ data from Figure 9 are shown plotted together with the pre-1986 control criteria based on 0.8 to 1.2 of the optimum moisture content and the current end product specification based on 95% of the maximum dry density. The data in Figure 9 indicates that approximately 92% of the results lie on or above the 95% compaction limit. Clarke and Coombs go on to suggest that a method specification, developed from an initial site trial with defined end product criteria, could be used, with routine acceptability determined by moisture content measurement. This would appear to be entirely appropriate for general fills. Note that this was acceptable up to 1986 and many engineered fills built prior to that still exist and function as designed.

Thus, treating pulverised-fuel ash as a manufactured material and using a Specification designed for such material can discourage its use. Other variable materials are currently more acceptable because the Specification is less onerous since they are placed in different categories.

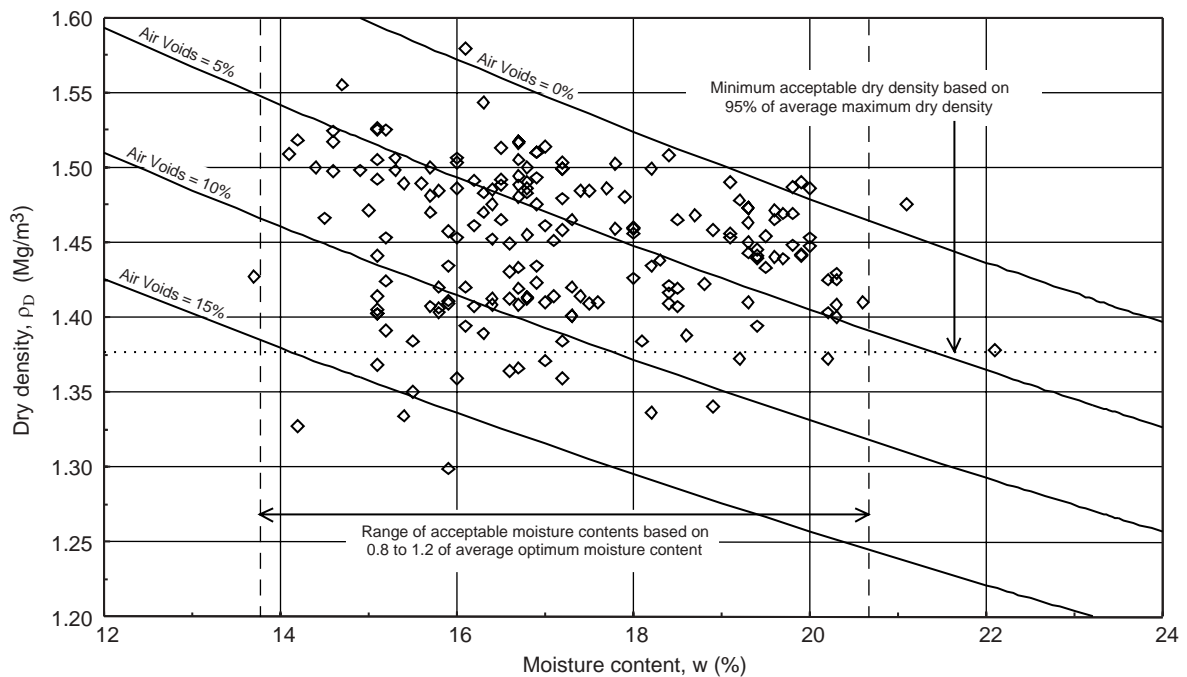


Figure 9 Control criteria compared to *in-situ* measurements

4.4 Construction issues

As the current Specification requires an end product for pulverised-fuel ash general fill no advice on appropriate compaction plant is given. However, experience would indicate that vibratory rollers are effective in use on pulverised-fuel ash. (Pneumatic-tyred rollers generally are also considered suitable, but there is relatively little experience of their use in the UK.) Smooth wheeled rollers (or vibratory rollers operating without vibration) are not generally recommended.

Clause 608 of MCHW 1 deals with the construction of fills and requires that a starter layer of Class 6D fill is placed above ground level where it is intended that the fill above is to be a Class 2E pulverised-fuel ash material. Class 6D is a selected uniformly graded granular material with 100% passing 10mm and between 0% and 15% at 150mm (between 0% and 20% at 150mm for crushed rock).

The Specification also allows the Engineer to specifically exclude the use of pulverised-fuel ash within a certain dimension below the sub-formation or formation, and the DMRB (Clause 5.59) recommends a minimum exclusion depth of 600mm. This exclusion is based on the following reasoning:

- Because of the grain shape and size (Figures 5 and 6) the upper layers of pulverised-fuel ash are difficult to compact (where field densities are being taken it is recommended that the top 100mm of pulverised-fuel ash is removed before testing). This is due to over-stressing during compaction. Compaction of the subsequent layer will remedy this effect;
- Freshly placed pulverised-fuel ash behaves in a manner similar to a pure silt and, if not protected, may liquefy following wet conditions;

- Capping and sub-base materials tend to be relatively permeable and a layer of general fill over pulverised-fuel ash is considered desirable to provide some protection.

Completed slopes of Class 2E and 7B fill material are required to be immediately covered by Class 5 topsoil, turf or other material in order to obviate the particular problem of erosion where pulverised-fuel ash embankments are exposed to the weather. Indeed, this is also standard practice in the construction of pulverised-fuel ash lagoon dams (Figure 10).

Typically, it is required that all permanent faces of side slopes formed from Classes 2 and 7 (cohesive) materials are re-worked and sealed, prior to trimming. This requirement does not apply to pulverised-fuel ash since pulverised-fuel ash, once compacted, can be easily disturbed. Disturbing pulverised-fuel ash once compacted can lead to zones of potentially low density and correspondingly high air voids within the compacted fill volume. These may be prone to significant future settlements on, for example, the ingress of water.

4.5 The case for a new approach to the specification

Pulverised-fuel ash is treated as a manufactured material in the Specification. This requires the Engineer to keep a record of the sources, and places the onus on the Contractor to provide the requisite control data including the natural moisture content, and the optimum moisture content and maximum dry density of each consignment. An end product specification is required for pulverised-fuel ash fill rather than the method specification that is applied to natural fills. This is justified by the inherent variability of pulverised-fuel ash, both between sources and from a single source on a day-to-day basis. The specified protocol for end product control can take up to



Figure 10 Construction of a pulverised-fuel ash disposal lagoon dam. Note that the sideslopes are in the process of being covered to provide protection from the weather

two days. While the Specification does not cover design methods it does recommend tests to produce design parameters. Design methods, which are not material specific, are either based on global or partial factors of safety using characteristic material properties. The procedure followed to determine pulverised-fuel ash properties imposes controls that result in worst case scenarios, not characteristic values. Thus, design methods and test procedures are not consistent.

Whilst it is accepted that pulverised-fuel ash is an inherently variable material and that this approach may be justified for selected fills, including structural fill, it can discourage the use of pulverised-fuel ash as a general fill. The approach taken to use pulverised-fuel ash as general fill in the Specification is at odds with that taken for natural soils, which are also inherently variable materials. In order to encourage the increased use of pulverised-fuel ash, a new method-based specification needs to be developed and introduced for general fill. In parallel to the new specification for site operations, there is a need for a consistent design procedure, thus enabling the wider use of pulverised-fuel ash with the associated environmental benefits.

The presence of carbon in pulverised-fuel ash affects its water absorption value and, as this has an influence on the calculated air voids value, makes the setting of limits in terms of air voids for compaction inappropriate. In addition it is clear from Figure 9 that 95% of maximum dry density corresponds to air voids values up to approximately 15%. While this level of air voids is higher than is normally required for natural fills, the current end product specification requires compaction to achieve 95% of the maximum dry density. Therefore this level of compaction is appropriate to form the basis of the proposed method specification. It must be remembered that this is the basis of the current end product specification and has been successfully applied since its introduction in 1986 (SHW, 1986).

High carbon contents can also effect the operation of nuclear density gauges. As such these devices should only be used in situations where an adequate calibration can be established between measurement made using the gauge and sand replacement tests.

The new approach to the Specification for pulverised-fuel ash as general fill is based upon site-specific trials to determine a suitable compaction method. It is recommended that initially Method 3 (MCHW 1, Table 6/4) compaction be used in the trials. This method was applied to pulverised-fuel ash before the introduction of the 1986 specification. However, limits on the type of plant allowed should be applied as detailed in Section 5.2.

It is intended that the trials be used to gather data on successful methods of compaction to allow further modification of the MCHW 1. Data and interpretations of the data should be sent to the United Kingdom Quality Ash Association. They will arrange for the collation of the data sets to form a fully method-based specification, once a sufficient amount and variety of data is available.

The specification is presented in Section 5 and guidance on the use of pulverised-fuel ash is given in Section 6. It is intended that the trial element of the specification be removed once sufficient data is available to form a robust method specification.

5 Specification using the new approach

The new approach to the specification of the use of pulverised-fuel ash as general fill is structured as amendments to the Specification for Highway Works and the associated Notes for Guidance on the Specification for Highway Works (MCHW 1 and 2). (MCHW 1 comprises a specification for a variety of earthwork materials including general fill, selected fill and fill to structures.)

It is recommended that the Specification be used in two ways. First, as a simple revision to contracts requiring the

use of MCHW 1 and 2. Second, that the Specification be used on contracts which would not normally require the use of MCHW. The Specification is recommended by virtue of it having been especially prepared for use with pulverised-fuel ash as general fill.

A commentary to the proposed Specification changes is given in Section 5.1. This details the reasoning behind each change and details the actual changes. Each relevant clause of MCHW 1 and 2 is addressed in Sections 5.2 and 5.3 respectively. Where change is required the relevant clause or part of the clause is re-written. Only relevant clauses are cited (i.e., those that have an impact on the use of pulverised-fuel ash as general fill), the requirements of all other clauses should be observed as necessary and relevant. Where it is felt that confirmation of no change to the MCHW specification is helpful this is given in Section 5.1.

5.1 Commentary on changes to MCHW 1 and MCHW 2

Clause 601: Classification, Definitions and Uses of Earthworks Materials

Sub-Clauses 601.17 and 601.18 are to be replaced by those given in Section 5.2.

Sub-Clause 601.17 confirms that pulverised-fuel ash should not normally be placed within a given depth below sub-formation or formation, unless an impermeable geosynthetic separator or bound layer is to be placed immediately above the sub-formation or formation. In the existing Specification this depth is left entirely to the Specifier's discretion although the Design Manual for Roads and Bridges makes a strong recommendation that it should be 600mm. The revision makes 600mm the default depth in the Specification (except as noted above), while leaving the option to alter this depth (see also Section 4.4).

Sub-Clause 601.18 makes modifications to lessen the onerous conditions placed upon the supply of pulverised-fuel ash whilst fully retaining the need to ensure compliance with the acceptability requirements of Table 6/1.

All other sub-Clauses in Clause 601, including sub-Clause 601.7, remain unchanged.

Clause 602: General Requirements

Clause 602 remains unchanged.

Clause 608: Construction of Fills

Sub-Clauses 608.2, 608.10 and 608.11 are to be replaced with those given in Section 5.2. These replace Class 2E 'Reclaimed pulverised-fuel ash cohesive material' with a new Class 1D 'Reclaimed or conditioned pulverised-fuel ash granular material' (see also Table 6/1).

The specification refers to pulverised-fuel ash as a cohesive material due to its relatively fine grain size. However, pulverised-fuel ash is silt-sized and thus coarser than clays, and, in some circumstances will behave more like a cohesionless, or granular, material. Pulverised-fuel ash is non-plastic. For example, the permeability of pulverised-fuel ash is very low and therefore it can be classed as a fine-grained material when considering flow

of water. Pore pressures dissipate within the construction period therefore, as far as strength is concerned, it can be classed as a coarse-grained material when considering the design of a pulverised-fuel ash structure. In that case the design parameter is the angle of shearing resistance, the parameter used for cohesionless materials.

Under this regime Class 1D pulverised-fuel ash is the only Class 1 material that may have >15% fines (particles passing 63µm). This does not present a problem of itself, especially as both the existing Class 2E and the new Class 1D material proposed herein, are not subject to a specific grading requirement other than that the maximum particle size shall be <3mm (Clause 601.7). In the longer term it may be desirable for the MCHW 1 and 2 to move away from the cohesive/granular descriptions of fill materials to fine-grained/coarse-grained. Pulverised-fuel ash would thus remain as part of the Class 2 fine-grained series of materials, but without the current implication as to behaviour.

Sub-Clause 608.13 remains unchanged.

Clause 612: Compaction of Fills

Sub-Clauses 612.16 to 612.30 are to be added to the Specification.

These make provision for a trial to be conducted to demonstrate the efficacy of pulverised-fuel ash as a general fill material and to determine the method of compaction to be used in the construction of the Permanent Works. The trial methodology is broadly based on that given in DMRB 4.1.5. The use of either sand replacement or nuclear methods of density determination is permitted. Special provision is made for the removal of the effects of the relatively uncompacted top 100mm of each layer of pulverised-fuel ash from the determination of density. If the sand replacement test is used then this must be achieved by physically removing the top 100mm. However, if the nuclear density gauge is used then the equation given for this purpose in sub-Clause 612.23 may be used. The derivation of this equation is given in Appendix A to this report.

The data presented in Figure 9 gives a maximum air voids value of approximately 15% at 0.8 times the average optimum moisture content and 95% of the average maximum dry density (assuming a particle density of 2.1Mg/m³). This implies that embankments can be successfully built and remain stable with at least some of the material forming the construction compacted to such low levels. Accordingly a target for the trial corresponding to 95% of the maximum dry density is set. Acceptability for the main earthworks operation is, initially, to be determined by the range of moisture content between 0.8 and 1.2 times the optimum.

It is intended that the trials be used to gather data on successful methods of compaction. Once sufficient data are available they should be used to determine a range of successful methods of compaction (combinations of layer thickness, number of passes, type and mass of plant) for pulverised-fuel ash to allow a new method for pulverised-fuel ash to be added to MCHW 1 Table 6/4.

Clause 616: Preparation and Surface Treatment of Formation

Sub-Clause 616.5 is to be replaced by that given in Section 5.2.

This replaces Class 2E 'Reclaimed pulverised-fuel ash cohesive material' with a new Class 1D 'Reclaimed or conditioned pulverised-fuel ash granular material' (see Table 6.1). For an explanation of this change see the commentary on Clause 608 in this section.

Clause 618: Topsoiling, Grass Seeding and Turfing

Sub-Clause 618.5 is to be added to the Specification.

As pulverised-fuel ash can have a relatively high boron content, this ensures that the boron content is assessed and where high boron contents are anticipated then boron resistant planting is used.

Clause 636: Determination of Effective Angle of Internal Friction (ϕ') and Effective Cohesion (c') of Earthworks Materials

Sub-Clause 636.6 is to be added to the Specification. This sub-Clause deals with the shear strength testing of Class 1D general fill material. However, many of the principles set-out in this clause are equally applicable to pulverised-fuel ash used as selected fill and the sub-Clause may, with care, be applied in place of sub-Clause 4, which deals with Class 7B pulverised-fuel ash selected fill.

The Specification refers to pulverised-fuel ash as a cohesive fill but herein it is treated as a granular material for the reasons given under Clause 608 above.

The self-hardening of pulverised-fuel ash due to the pozzolanic reaction between the particles and free lime results in the development of cementitious bonding which in turn results in a strength gain. Specimens need to be cured before testing to realise this strength gain. This gain in strength can be permanent and affects the effective strength parameters (cohesion and angle of internal friction).

While direct shear tests are specified, it is possible to carry out triaxial tests on suitable ashes. The results from the tests will differ from those from the direct shear tests because the test procedure is different, but within the natural variability of the material the differences may not be critical.

Clause NG 612.2: Compaction of Fills

Sub-Clause NG 612.2 is to be replaced with that given in Section 5.3.

This removes the requirement for end product compaction for pulverised-fuel ash in general fill.

Sub-Clause 612.3 is to be added to the Notes for Guidance on the Specification.

This confirms the requirement for a compaction trial to be carried out prior to the use of pulverised-fuel ash in general fill.

Clause NG 636: Determination of Effective Angle of Internal Friction (ϕ') and Effective Cohesion (c') of Earthworks Materials

Sub-Clauses NG 636.4 to NG 636.6 are to be added to the Notes for Guidance on the Specification.

The critical state angle of internal friction taken from tests carried out immediately after compaction is normally selected and a limit to the cohesion of 5kPa is applied. Some ashes show a permanent gain in strength with time. That gain in strength is also accompanied by an increase in brittleness. For that reason the most likely worst conditions are selected, that is the post-peak strength. In practice, there is an increase in strength with time for some ashes. The increase in permanent strength should be taken into account and can be justified since the test conditions still represent the most likely worst conditions. There should be no restriction on the value of cohesion provided the post-peak value is chosen. Peak failure ensures that any temporary bonds are destroyed. The post-peak angle of internal friction also increases with time.

NG Sample Appendix 6/3: Requirements for Excavation, Deposition, Compaction (Other Than Dynamic Compaction)

Item 6(iv) is to be added to the Specification. This confirms the requirement for a compaction trial to be carried out prior to the use of pulverised-fuel ash in general fill and allows for the use of a nuclear density gauge in the measurement of the trial.

Table 6/1: Acceptable Earthworks Materials: Classification and Compaction Requirements.

Class 2E is to be deleted and Class 1D to be added.

For an explanation of this change see the commentary on Clause 608 in this section.

Table 6/2: Grading Requirements for Acceptable Earthworks Materials

Table 6/2 is unchanged.

Table 6/4: Method Compaction for Earthworks Materials: Plant and Methods. (This Table is to be read in conjunction with sub-Clause 612.10.)

Table 6/4 is unchanged.

5.2 Specification for Highway Works

Clause 601: Classification, Definitions and Uses of Earthworks Materials

17 Pulverised-fuel ash shall not be placed within 600mm below (or other depth specified in Appendix 6/3) sub-formation or formation, unless an impermeable geosynthetic separator or bound layer is to be placed directly upon the sub-formation or formation.

18 Where pulverised-fuel ash is used the Contractor shall ensure that supplies to site are consistent in terms of type and source, and that the acceptability limits applied are appropriate to the material as supplied. The type and source of the material and the name of the power station from which it is obtained shall be recorded.

Clause 608: Construction of Fills

- 2 Starter layers of Classes 6B, 6C or 6D materials as described in Appendix 6/3 shall be deposited as the first layer or layers of fill above existing ground level or, if appropriate, above any ground improvement required by Appendix 6/13. Starter layers below Class 1D pulverised-fuel ash general fill shall be Class 6D material. Plant movement across starter layer material shall be restricted to that plant which is necessary for its deposition, spreading and compaction in compliance with this Clause and Clause 612 and any plant required to carry out ground improvement beneath it if required by Clause 630. The Contractor shall take all reasonable measures to prevent damage to the underlying strata, which may include the use of lighter spreading plant or a reduction of the number of passes of compaction plant.
- 10 During construction of embankments and other fills, exposed sides of Classes 1D and 7B pulverised-fuel ash material shall be protected against scour and erosion from any source.
- 11 Completed slopes of Classes 1D and 7B fill material shall be covered immediately by Class 5 topsoil as required in Appendix 6/8 or turf or other material, as required in Appendix 30/5.

Clause 612: Compaction of Fills

Demonstration Trials for Pulverised-fuel Ash General Fill

- 16 The trial area shall be located on material compacted in accordance with sub-Clauses 612.1 to 612.10 to a depth of at least 1m and should be constructed prior to the commencement of the main fill operations. The material to be used for the trial shall be of the same type and source, and obtained from the same power station as the material proposed for use in the Permanent Works. The information described in sub-Clause 12 of this Clause shall be supplied.
- 17 The trial area should measure approximately 15m to 20m in length and be of a width equal to at least four times the overall width of the largest item of plant to be used.
- 18 The trial area shall be divided into two equal widths and acceptable pulverised-fuel ash material as defined in Clause 601 and by Class 1D in Table 6/1 deposited over each half. The depth of material deposited and the number of passes to be applied shall be determined initially from Method 3 in Table 6/4. However, vibratory rollers and pneumatic-tyred rollers are known to be particularly effective in compacting pulverised-fuel ash and success may be possible with larger pneumatic tyred rollers than is indicated by Method 3.
- 19 The two trial areas should be used to trial two depth/ number of passes combinations, or two types of plant as appropriate to the Contractor's proposed site operations. Notwithstanding this, care shall be taken to ensure that uniform conditions are achieved over the whole trial area.
- 20 The trial shall then be compacted according to the Contractor's proposed site operations. Acceptability of

the trial material shall be on the basis of moisture content relative to the compaction curve determined in accordance with the BS1377: Part 4, 2.5kg rammer method. A minimum of five measurements of the maximum dry density and optimum moisture content shall be made, and the average of each taken. Samples for compaction tests shall be composites of spot samples taken from pulverised-fuel ash at the time of delivery, not from material that has been placed and compacted. The lower limit for moisture content shall be defined as 0.8 times the average optimum moisture content. The upper limit shall be 1.2 times the average optimum moisture content. Other approaches to determining acceptability limits may be used subject to the approval of the Employer's Representative.

- 21 After compaction, determinations of the state of compaction, in accordance with the sand-replacement method or by nuclear gauge methods as described in BS1377: Part 9 shall be made in each half of the compacted area. Other density measurement techniques may be used with the prior written approval of the Employer's Representative.
- 22 Where the sand-replacement method is used then the upper 100mm of pulverised-fuel ash shall be removed prior to test.
- 23 Where nuclear methods are used, the gauge shall be calibrated in accordance with BS1377: Part 9. Measurements of density shall be made in direct transmission mode at each possible point through the layer. Either the upper 100mm shall be removed prior to test or the effects of the upper 100mm eliminated using the following equation:
$$\rho_i = [z_i \bar{\rho}_i - z_{i-1} \bar{\rho}_{i-1}] / (z_i - z_{i-1})$$
where $\bar{\rho}$ is the average density measured from the surface of the compacted layer to regularly spaced (usually 25mm) depth increments,
 ρ is the required average density between each adjacent pair of depth increments,
 z is the depth of the increments, and
 i represents the increments from 1 to n .

The calculated, discrete average densities for each measurement point through the layer shall be calculated, those representing the uppermost 100mm of the compacted layer eliminated and the average layer density calculated from the remaining data.

- 24 Sufficient tests to determine the average layer density shall be carried out in each half of the compacted area to yield results on which decisions can be made on a sound statistical basis. A minimum of ten measurements of the average layer density shall be made.
- 25 Once sufficient tests have been conducted and a high degree of confidence in the average applicable to each test area has been demonstrated, the Contractor's proposed method must either be approved or otherwise. If at least nine out of every ten measurements of the average layer density indicate a dry density $\geq 95\%$ of the maximum (determined from the BS1377: Part 4, 2.5kg rammer

method) then the Contractor's proposed method shall be approved, unless there are exceptional reasons for not doing so. Such exceptional reasons must be clearly stated by the Engineer or Employer's Representative.

- 26** Acceptability limits for the main fill operation shall be set in terms of a maximum and minimum moisture content range. These shall be based upon those used for the trial (see sub-Clause 612.20), modified as necessary and appropriate in the light of the trial results.
- 27** If the Contractor cannot achieve adequate compaction (as defined in sub-Clause 612.25) using an initial suggested method, then either increasing the compactive effort or alternative combinations of layer thickness, compaction plant and number of passes considered for re-trial may be considered. If the trial(s) do not yield sufficient compaction then the Contractor's proposed method shall not be approved.
- 28** The materials placed during the trials may form part of the Permanent Works, provided they meet the requirements of the Contract or be carried out elsewhere on the Site where this is detailed in Appendix 6/7.
- 29** The trial area shall, if it does not meet the requirements of the Permanent Works or is located elsewhere on site, be removed and the area reinstated in Accordance with Appendix 6/7.
- 30** The materials and plant used in the accepted trial shall not be changed during the construction of the Works without the construction of a further trial. For this purpose the maximum dry density and optimum moisture content shall be determined periodically. Some variation in the results should however be expected.

Clause 616: Preparation and Surface Treatment of Formation

- 5** The Contractor shall limit any areas of completed formation to suit the output of the plant in use and the rate of deposition of sub-base. No formation of granular material Class 1D, or cohesive material Classes 2 and 7 shall remain continuously exposed to rain causing degradation or be left uncovered overnight.

Clause 618: Topsoiling, Grass Seeding and Turfing

- 5** Suppliers shall supply details of the boron content of pulverised-fuel ash such that an assessment of vegetation suitable for growth over areas of Class 1D pulverised-fuel ash fill can be made. Where high boron contents are anticipated then all planting and seed mixtures shall comprise boron resistant strains.

Clause 636: Determination of Effective Angle of Internal Friction (ϕ') and Effective Cohesion (c') of Earthworks Materials

- 6** For Class 1D pulverised-fuel ash granular material the effective angle of internal friction and effective cohesion shall be determined using shear box tests carried out in accordance with BS1377: Part 7 (Method 5) and the following:

- (i) The plan size of the shear box shall be nominally 300mm square. Alternatively, if powdered pulverised-fuel ash is used then the test can be carried out in a 100mm shear box (BS1377: Part 7: Method 4), but otherwise conducted as described below.
- (ii) Specimens shall be compacted into split moulds that fit within a 305mm direct shear box or directly into the shear box. The method followed is that for partially saturated cohesionless soil using the 2.5kg compaction method described in BS 1377: Part 4. Each sample shall occupy the full depth of the shear box and shall be compacted at the maximum dry density and optimum moisture content. The specimens shall be sealed and stored for a minimum of fourteen days before testing.
- (iii) A minimum of three specimens shall be prepared. These shall be tested at normal stresses of 20kPa, 50kPa and 100kPa to represent the typical range of stresses within an embankment. If the proposed fill is deeper than 5m then the normal stresses shall be increased to reflect the increased load.
- (iv) Specimens shall be soaked for 24 hours before shearing. The test procedure shall be that specified in BS1377: Part 7, except that shearing shall continue until the full travel of the apparatus has been reached. The rate of shearing shall be calculated from the consolidation stage using the criteria for a slow test in BS1377: Part 7 and shall be no faster than 1.5mm/min and the displacement at failure shall be at least 30mm (10% of the plan dimension of the specimen).
- (v) The pulverised-fuel ash may contain agglomerated particles or agglomerated particles may form during curing. For that reason each specimen shall be used only once.
- (vi) BS 1377: Part 7 specifies the data required for each test. In addition the maximum shear stress, the displacement relative to the box dimension (horizontal strain) at that stress and the post-peak stress shall be quoted.
- (vii) The peak and post-peak values of shear stress shall be plotted against the normal stresses. The best-fit lines to these two sets of data shall be plotted and the intercept, the cohesion, the angle of the slope, and the angle of internal friction, shall be determined for both peak and post-peak conditions.

5.3 Notes for Guidance on the Specification for Highway Works

Clause NG 612.2: Compaction of Fills

- 2** End product compaction is restricted to some selected fills to structures including corrugated steel buried structures. Density testing of the materials to be used will be necessary in order to comply with an end product specification.

- 3 Granular general fill Class 1D pulverised-fuel ash is subject to trials at the commencement of construction in order to demonstrate that adequate compaction can be achieved.

Clause NG 636: Determination of Effective Angle of Internal Friction (ϕ') and Effective Cohesion (c') of Earthworks Materials

- 4 Class 1D pulverised-fuel ash comprises silt size particles that together behave as a granular material. The chemical composition of the pulverised-fuel ash changes with time due to pozzolonic action. This results in a gain in strength. Thus specimens need to be cured before testing to realise this strength gain. The chemical changes that contribute to this strength gain include soluble and insoluble components. For this reason, specimens shall be soaked before testing to ensure that strength measured represents the most likely worst condition.
- 5 While Class 1D pulverised-fuel ash is a silt size material, reclaimed ashes may contain agglomerated particles. The minimum size of specimen that can be tested to provide realistic results depends on the maximum particle size. For that reason it is normal to specify nominal 300mm direct shear tests. All particles greater than 20mm shall be removed. The proportion of particles greater than one tenth of the height of the specimen shall not exceed 15%.
- 6 While direct shear tests are specified, it is possible to carry out triaxial tests on suitable ashes. The results from the tests will differ from those from the direct shear tests because the test procedure is different. The rules on particle sizes still apply. Triaxial specimens may be easier to prepare and cure since cylindrical moulds can be used. The procedure followed shall conform to BS1377: Part 8 except that curing, soaking and other procedures detailed in Clause 636 and NG 636 shall be followed.

NG Sample Appendix 6/3: Requirements for Excavation, Deposition, Compaction (Other Than Dynamic Compaction)

Add item 6(iv), as follows:

6

- (iv) Compaction Trials for Class 1D Materials:
- (a) The use of a nuclear surface density gauge shall normally be permitted (unless there are pressing reasons for exclusion) subject to the conditions set-out in Clause 612.23. However, nuclear density gauges may only be used if an adequate calibration between measurements made using the gauge and the sand replacement method on the pulverised-fuel ash in question can be established.

Table 6/1 Acceptable earthworks materials: classification and compaction requirements

Class	General material description	Typical use	Permitted constituents (all subject to requirements of Clause 601 and Appendix 6/1)	Material properties required for acceptability (in addition to requirements on use of fill materials in Clause 601 and testing in Clause 631)				Compaction requirements in Clause 612	Class
				Property (see exceptions in previous column)	Defined and tested in accordance with:	Acceptable limits within:			
				(i) mc	BS1377: Part 2	Lower	Upper		
1D	Reclaimed or conditioned pulverised-fuel ash granular material	General fill	Fresh conditioned material direct from the power station hopper or reclaimed material from lagoon or stockpile containing not more than 20% furnace bottom ash	(ii) bulk density	BS1377: Part 9	App 6/1	App 6/1	Clause 612.16 to Clause 612.30	1D

6 Guidance

This section gives detailed guidance to help ensure that the use of pulverised-fuel ash as general fill is carried out in an appropriate manner from the point of view of earthwork stability, economy, environment, and health and safety.

The guidance is drawn from a variety of sources, including DMRB 4.1.1, UKQAA (2000), Coombs and Sear (2000) and the experience of the authors and UKQAA members.

6.1 Health and safety

The suppression of dust is addressed in the following sections. More specific issues in relation to pulverised-fuel ash, particularly in relation to the COSHH Regulations 1994, are dealt with in more detail by UKQAA (2000) and this document should be referred to at an early stage of a proposed project.

Dry pulverised-fuel ash in normal use has no harmful effect on dry skin. Precautions should, however, be taken to avoid entry to the eyes, mouth and nose and to prevent skin contact with wet pulverised-fuel ash. When working in places where dry pulverised-fuel ash becomes airborne, protection for the eyes, nose and mouth should be worn. If pulverised-fuel ash enters the eye it should be immediately washed out thoroughly and medical treatment sought without delay.

Although no connection has been established between pulverised-fuel ash and dermatitis, this possibility cannot be ruled out. Continued contact during the working day can lead to alkali burns with ulceration, but this is not common (BS 3892: Parts 1 and 2).

6.2 Environmental issues

Environmental issues in relation to the use of pulverised-fuel ash as fill are described by UKQAA (2000) and Coombs and Sear (2000) and should be referred to at an early stage in the planning of a proposed project.

6.3 Investigation, design and testing

Potential sources of pulverised-fuel ash for use as general fill should be treated in the same manner as any other potential source material. Supplier data should be requested and studied at the preliminary ground investigation stage and physical samples recovered for testing at the appropriate stage of the investigation.

As with natural materials, it is important that pulverised-fuel ash sources are treated as masses with variable properties. Investigation, sampling and testing should reflect these facts. It is particularly important to consult with potential suppliers as to potential variability within stockpiles or lagoons caused by changes in coal supply or processing method.

There are particular requirements with regard to the testing of pulverised-fuel ash and these apply to the testing of pulverised-fuel ash at the investigation, design and construction stages. These requirements are as follows:

- 1 Dust control: Compaction tests (for example) at moisture contents so low as to allow excessive amounts

to be carried to atmosphere should be avoided where possible. Where dust is found to be a problem provision should be made to allow the extraction of such dust and protective masks made available.

- 2 Over-stressing during compaction: Due to over-stressing during compaction the upper layers of pulverised-fuel ash are difficult to compact. Where field densities are being taken it is recommended that either the top 100mm of pulverised-fuel ash is removed before testing or, if a nuclear density gauge is used, that the effects of over-stressing are removed from the calculation of average layer density by numerical means. For tests on pulverised-fuel ash an additional layer is recommended. This is to be removed at the end of the test - conventional tests and the modified test for pulverised-fuel ash are illustrated in Figure 11.
- 3 Strength properties: The design of slopes constructed from pulverised-fuel ash and the bearing capacity of foundations in pulverised-fuel ash should be based on effective strength parameters. Pulverised-fuel ash is a silt-sized material. Therefore it is possible to carry out consolidated drained or undrained triaxial tests. The Specification suggests large shear box tests. These are easier to perform and will be necessary if the pulverised-fuel ash contains any agglomerated particles; agglomerated particles can occur in stockpiled ash because of pozzalanic action (Figure 6). Tests should be carried out on three separate specimens, each prepared at the maximum dry density and optimum moisture content. The specimens should be sealed and stored for at least 14 days before testing to allow for any permanent gain in strength. Specimens should be soaked for 24 hours before consolidating and shearing. Consolidated drained tests are preferred. The rate of shearing should be slow enough to prevent excess pore water pressures developing. Guidelines are given in BS 1377: Part 8. The three specimens should be consolidated to three different pressures to represent the range of pressures through the depth of fill; 25kPa, 50kPa and 100kPa is a typical range. Shearing should be continued until the post-peak strength is achieved. It is the post-peak strength that should be used for design. The failure envelope should be a tangent to the three Mohr's circles representing the post-peak stresses. The angle of friction is taken as the slope of that line; the cohesion, which should be positive, is the intercept on the vertical axis.

6.4 Supply

In general terms, reclaimed pulverised-fuel ash from stockpile or lagoon has more consistent compaction properties and will thus be more suitable for use as general fill. The use of conditioned ash should not be discounted as some sources can be as consistent as reclaimed materials. This emphasises the need to consult with potential suppliers well in advance of the requirement for pulverised-fuel ash general fill.

There is a further issue in relation to the preference of reclaimed over conditioned ash. Conditioned ash has a greater potential to be used in higher value applications,

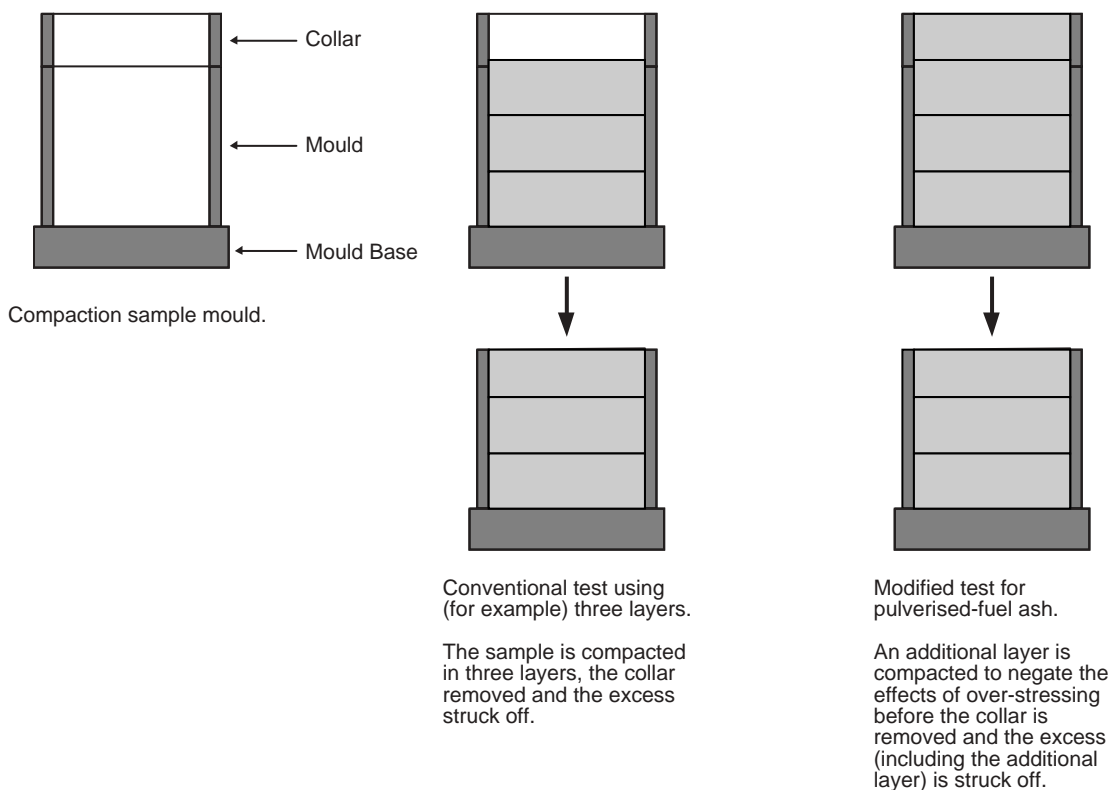


Figure 11 Compaction test procedures to negate the effects of over-stressing: sample mould equipment (left); conventional test on material not subject to over-stressing (centre); and test for pulverised-fuel ash and other material subject to over-stressing (right)

such as cement mixes, and thus may be more difficult to obtain (Winter and Henderson, 2001). In addition it is not possible to investigate sources in advance of construction other than if it is assumed that supplies will remain consistent - this is not always the case and changes in coal source and processing methodology may yield significant changes to the pulverised-fuel ash by-product.

Some pulverised-fuel ash supplies have high boron contents. This can inhibit the growth of some plant species. Data on the boron content of pulverised-fuel ash should be available from the suppliers and this should be examined such that an informed opinion can be formed on the type of plants to be used. If a high boron content is anticipated then boron resistant strains of plant should be used. Decisions of this nature must often be taken at an early stage in any contract, possibly at the design stage, due to the length of time required to grow suitable specimens.

6.5 Supply monitoring and acceptability

Monitoring of supplies can be approached on the same basis as for natural fills. The DMRB 4.1.1 gives advice on the frequency of testing, whilst also noting that definitive guidance is inappropriate as the testing regime should be tailored to the specific situation. Testing is recommended at the following frequencies:

- 1 Compliance of supply - compaction curve and particle density: twice a week.
- 2 Acceptability - moisture content for comparison with the compaction curve: one to two tests per 1000m³ up to a maximum of five per day.

Testing should be carried out in accordance with the appropriate British Standard with the exception of the modifications recommended in Section 6.3 above.

In addition, the moisture content of pulverised-fuel ash can be roughly checked by visual inspection. Pulverised-fuel ash moulded in the hand should form a single and coherent mass when reasonable pressure is exerted, and no moisture should be squeezed out. Material that is too wet will show signs of drainage, ranging from a shiny and 'glistening' surface to water squeezing out of the mass under such pressure. Material that is too dry will not hold together as a coherent mass under reasonable pressure.

Materials that do not conform to specification requirements should be treated in the same way as for natural fills.

6.6 Transport, placement and compaction

The keys to the transport and placement of pulverised-fuel ash are dust suppression and maintenance of the moisture content.

Transport of pulverised-fuel ash must be undertaken in covered wagons in order to minimise the creation of dust and its consequent deposition on public roads and other areas. Ensuring that the material is transported at a moisture content suitable for compaction (see above) will also help prevent the propagation of dust.

Placement of pulverised-fuel ash is usually best achieved by depositing the material to be compacted directly from the vehicle used to transport it from the source at the point at which it is required. If the material is

to be stockpiled prior to compaction then the amount should be kept to a minimum and the stockpile should be sprayed regularly in order to prevent dust problems caused by desiccation.

Spreading of large areas of pulverised-fuel ash is best achieved using a flat-tracked bulldozer (Figures 12 to 14). Indeed, ensuring that the surface of the pulverised-fuel ash is thoroughly tracked by the spreading plant can aid the compaction process when a vibratory roller is used and is essential if a pneumatic tyred roller is used. In either case the energy applied by the spreading process must not be used to reduce the number of passes applied by the compaction plant.

If part or all of the spreading process is to be carried out using hand tools then tarmac rakes should be used in preference to shovels.

Compaction plant, compacted layer thickness and number of passes should be determined as described by means of a trial to determine an appropriate method of compaction. Pulverised-fuel ash should be spread in loose layers and as a guide a loose layer approximating to 225mm will generally compact to 150mm.

Suppliers of pulverised-fuel ash will generally make every effort to ensure that a specified moisture content is achieved at the point of loading. However, transporting and placing the material may cause desiccation and in such case the pulverised-fuel ash should be sprayed during the spreading process and prior to compaction.

Clause 612.18 suggests that Method 3 compaction in the MCHW 1 (Table 6/4) should be used for the compaction of pulverised-fuel ash. This implies that a wide range of compaction plant can be used as the method is applicable to a wide range of materials other than pulverised-fuel ash. The most suitable plant for pulverised-fuel ash compaction have been found to be towed or self-propelled vibratory rollers. The compaction process should consist of not less than eight passes per layer (see also Clause 612.16 to 612.30). The first two passes should be without vibration and the remainder should be with vibration. The final pass should be in such a direction that any surface 'cracks' are tightened up (this is usually a reverse pass, but may depend on the slope). Sometimes an additional final pass without vibration will assist in closing up surface 'cracks'. It is essential that any 'cracks' formed in the surface of the compacted material are fully closed to prevent moisture ingress (see also Section 6.7).

There are reports of the successful use of self-propelled pneumatic tyred rollers being used in the compaction of pulverised-fuel ash. However, there is only limited experience of their use in the UK.

For more restricted areas tandem vibrating rollers and vibro-tampers have been found to be successful in the compaction of pulverised-fuel ash.

The following types of compaction plant have been found to be unsuitable for use with pulverised-fuel ash:

- Smooth wheeled (dead weight) rollers.
- Sheepsfoot rollers.
- Grid rollers.
- Vibrating plates.

6.7 Protection of earthworks

All fills require protection once constructed. In essence this revolves around protection from water ingress and from unnecessary trafficking. With pulverised-fuel these factors are particularly important and the protection of side slopes against water caused erosion is also important.

The Specification (MCHW 1: sub-Clause 602.15 and 602.16) places duties on the Contractor to keep earthworks free of water by arranging for the rapid removal of water shed on the earthworks and preventing water entering the earthworks from any source. In addition, where excavations are to be made in fill or in-situ materials the Contractor must ensure the water levels in excavations are sufficiently lowered and maintained by appropriate means to enable the construction of the Permanent Works. In carrying out these requirements the Contractor is required to:

- Form and maintain cuttings, embankments and other areas of fill with appropriate falls and gradients, and sealed surfaces.
- Provide, where necessary, temporary watercourses, drains, pumping and the like.
- Discharge accumulated water and groundwater into the permanent outfalls of the drainage system where practicable.
- Provide adequate means for trapping silt on temporary systems discharging into permanent drainage systems.

Of particular importance with pulverised-fuel ash earthworks is protection of side slopes against erosion. Completed slopes of pulverised-fuel ash fill material should be immediately covered by Class 5 topsoil, turf or other material (Figure 10) in order to obviate the particular problem of erosion where pulverised-fuel ash embankments are exposed to the weather.

Freshly placed pulverised-fuel ash behaves in a manner similar to a pure silt and, if not protected, may liquefy following wet conditions. Capping and sub-base materials tend to be relatively permeable and a layer of cohesive general fill or other impermeable material, such as an impermeable geosynthetic or bound layer, over pulverised-fuel ash is considered desirable to provide some protection.

Protection of pulverised-fuel ash against excessive trafficking is important as it can cause the surface to break-up and deteriorate. This has two detrimental effects:

- In dry conditions dust can be raised and become a problem.
- In wet conditions the surface may cut up and allow water ingress.

While these effects should be avoided if at all possible, if they do occur the Contractor must make all attempts to repair the earthworks. In dry conditions water may need to be added before re-compacting the surface, while in wet conditions the affected areas will need to be allowed to dry out before re-compacting the surface. If attempts at repair do not work then the affected material must be removed and replaced with fresh material in accordance with the Specification.

Permanent faces of side slopes formed from pulverised-fuel ash should not be re-worked and sealed, prior to



Figure 12 Pulverised-fuel ash compaction during construction of the A52 trunk road



Figure 13 Pulverised-fuel ash compaction during construction of a new flyover approach road on the A52 trunk road



Figure 14 Pulverised-fuel ash compaction during construction of the M1–A42 Link

trimming, since once compacted it can be easily disturbed. Disturbing pulverised-fuel ash once compacted can lead to zones of potentially low density and correspondingly increased air voids within the compacted fill volume. These may be prone to significant future settlements on, for example, the ingress of water.

Stable, successful pulverised-fuel ash general fill earthworks can be constructed. An example is given in Figure 15.

7 Summary

In the UK, the introduction of a tax on landfill and the tightening of planning consents for disposal provide powerful incentives for the use of industrial by-products such as pulverised-fuel ash in construction. However, the current commonly used Series 600, Specification for Highway Works and associated Notes for Guidance (MCHW 1 and 2) treat pulverised-fuel ash as a manufactured material and applies an end product specification for compaction.

A method specification is more commonly applied to natural fill materials used as general fill. The specification for pulverised-fuel ash requires that the maximum dry density and optimum moisture content are determined for each consignment of pulverised-fuel ash delivered to site: a process that can take up to two days. The introduction of a method-based specification for the use of pulverised-fuel ash as general fill would enable its greater use and thus reduce the UK-wide need for landfill.

In addition, the specification requires testing to determine effective shear strength parameters under fully saturated conditions for embankment design. No guidance on whether peak or post-peak parameters are to be selected for design purposes or, indeed, on appropriate factors of safety is given. As a result most engineers test pulverised-fuel ash in the fully saturated condition, select post-peak effective shear strength parameters for design and apply a conservative factor of safety. As the testing protocol represents a worst case scenario the application of such a conservative approach can be questioned.

The background to the need for increased usage of pulverised-fuel ash in the construction of general fill is described. The history and development of the Specification are also outlined. The current Specification (and associated documents) is described in some detail. From this the case for a new approach to the specification of pulverised-fuel ash is made. The new approach is set within the context of the current Specification for Highway Works and associated Notes for Guidance (MCHW 1 and 2), such that it can be simply and rapidly incorporated into these documents. The new approach is thus proposed as changes to MCHW 1 and 2 to encourage the greater use of pulverised-fuel ash in general fill, whilst ensuring the continued construction of stable earthwork structures. Guidance on the use of pulverised-fuel ash in general fill earthworks is also given

In this document pulverised-fuel ash for use as general fill is treated as a granular material. This is in contrast to

the current Specification (MCHW 1 and 2), which treats pulverised-fuel ash as a cohesive material. Accordingly there is a need to amend other elements of the Specification (i.e., Classes 7B, 7G and 9C selected fill) to reflect this change.

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Figure 15 Completed embankment constructed from pulverised-fuel ash on the A69 Extension near Newcastle

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Appendix A: Use of nuclear density gauges

Bulk density and moisture content (moisture density) may be measured using Nuclear Density Gauges (NDGs) with gamma and neutron sources respectively. Bulk density may be measured in both backscatter and direct transmission modes. Moisture content may be measured only in the backscatter mode (Figure A1). Backscatter takes place with both the source and detector at the surface, while in direct transmission mode the source is placed at depth within the material being measured and the detector remains at the surface.

Measurements made in the backscatter mode suffer the disadvantage that they represent only the top 135mm of material, with the main influence being centred about a depth of around 60mm (Figure A1). While this is generally acceptable for moisture content measurements it is far from ideal for density measurements in natural fill materials. Backscatter measurements of density are particularly inappropriate for pulverised-fuel ash, which is well known to compact poorly in the upper part of a layer. Direct transmission (Figure A1) is thus a prerequisite for the measurement of density in pulverised-fuel ash fill. Indeed as the direct transmission method returns measurements of the average density between the source and the surface detector some means of discounting the effect of the upper 100mm of the compacted layer is also highly desirable.

Average density is measured from the surface of the compacted layer to regularly spaced (usually 25mm) depths ($\bar{\rho}$). What is required is the average density between each adjacent pair of these points (ρ). If we assume that n measurements are made at equally spaced intervals of depth (z) from the surface of the compacted layer (Figure A2) then:

$$\bar{\rho}_n = \left[\sum_{i=1}^n \rho \right] / n \quad (1)$$

It can be shown that:

$$\rho_n = n\bar{\rho}_n - \sum_{i=1}^{n-1} \rho_i = n\bar{\rho}_n - (n-1)\bar{\rho}_{n-1} \quad (2)$$

Re-writing equation (2) in the general form for positional increments of $i = 1$ to n gives an equation that can be used to determine the average density between any two successive, equally spaced measurement points:

$$\rho_i = i\bar{\rho}_i - (i-1)\bar{\rho}_{i-1} \quad (3)$$

Equation (3) can thus be used to determine the density profile within a fill layer and allow the relatively uncompacted upper part of a pulverised-fuel ash layer to be neglected. The depths will be characterised by $z = 1$ to n where z is the incremental depth between successive measurement points. It is, however, important to understand that equation (3) is valid only if the depth intervals at which measurements are made are equally spaced.

The foregoing method is based upon that reported in a number of unpublished reports from the National Institute

for Transport and Road Research in South Africa. Published accounts of the method have not been traced, although the method has clearly been used in published works (e.g., Clifford, 1980). The main problem with the method is the requirement that the depth increments are equal. While nuclear density gauges are capable of making measure at equal increments of depth some machines cannot take measurements at the first measurement point (usually 25mm). In addition it is relatively easy for operators to omit some readings. In either case the depth increments cease to be equal and an approach allowing for this is then required. An approach for unequal depth increments also allows measurements to be made at certain depths in order to ascertain the density for distinct compacted layers that may be of unequal depth. In addition the method may also be applicable to other types of measurement that may not naturally yield measurements at equal depth intervals.

In the case where the depth intervals are unequal then the depth to each measurement point must be individually considered. This may be achieved by weighting the measured density by the depth over which it is measured. Similarly the calculated densities between measurement points may be weighted by the distances between the incremental depths.

Thus for $i = n$, where $\bar{\rho}_n$ is for z_0 to z_n and for z_{n-1} to z_n then

$$(z_n - z_0)\bar{\rho}_n = (z_1 - z_0)\rho_1 + (z_2 - z_1)\rho_2 + \dots + (z_n - z_{n-1})\rho_n \quad (4)$$

Rearranging equation (4) for ρ gives:

$$\rho_n = z_n\bar{\rho}_n - \left[\sum_{i=1}^{n-1} (z_i - z_{i-1})\rho_i \right] / (z_n - z_{n-1}) = [z_n\bar{\rho}_n - z_{n-1}\bar{\rho}_{n-1}] / (z_n - z_{n-1}) \quad (5)$$

Re-writing equation (5) in the general form for positional increments of $i = 1$ to n gives an equation that can be used to determine the average density between any two successive, unequally spaced measurement points:

$$\rho_i = [z_i\bar{\rho}_i - z_{i-1}\bar{\rho}_{i-1}] / (z_i - z_{i-1}) \quad (6)$$

A prerequisite for the use of NDGs with all materials is the provision of an adequate, material-specific calibration. This should be undertaken in laboratory conditions over the range of moisture contents and densities likely to be encountered in the field (BS1377: Part 9). The calibration process is especially important to the use of NDGs in pulverised-fuel ash due to the potential effects of high organic contents on the results obtained.

Twin-probe NDGs have been available on the market for some time now. These place both the source and detector at the same depth, negating the need for calculations of the type given above. The major disadvantages of such devices are their cost and the additional complexity of operation.

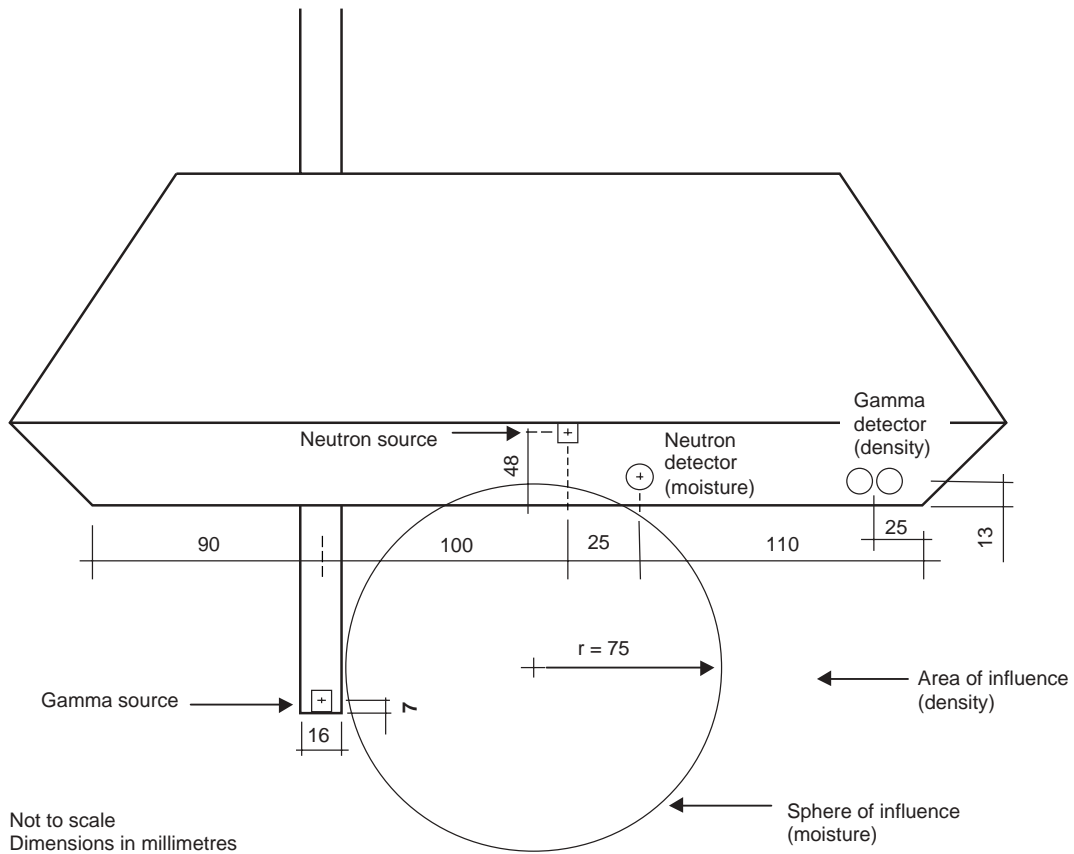


Figure A1 Layout of a typical nuclear density gauge showing the location of radioactive sources and detectors for moisture and density measurement

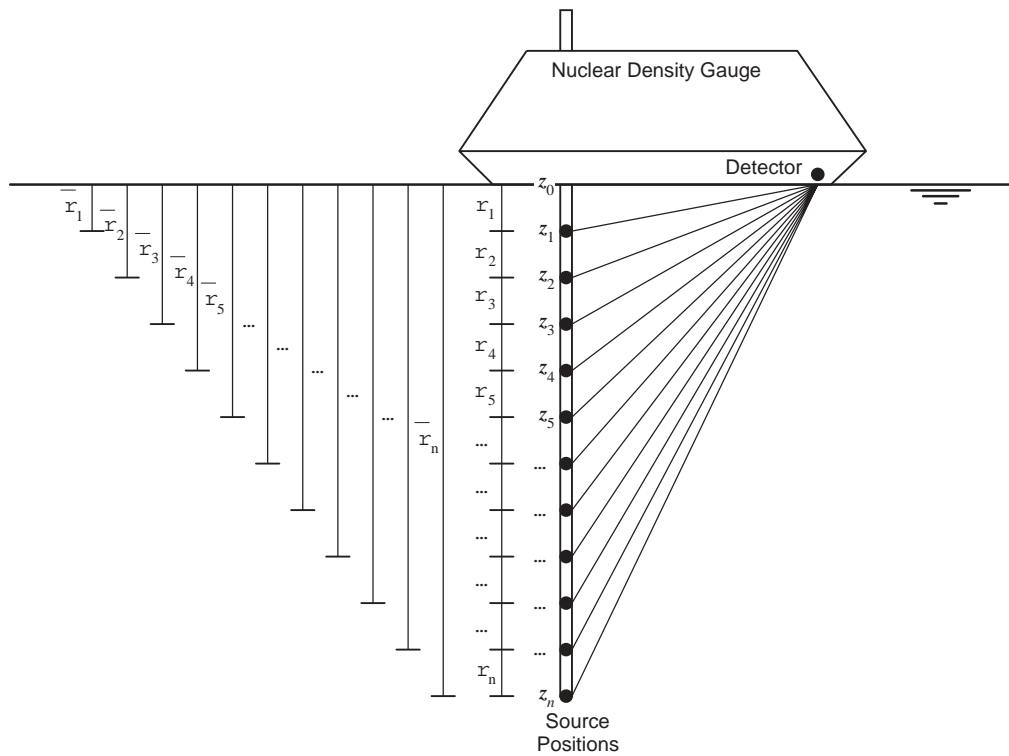


Figure A2 Nuclear density gauge operation showing density and mean density with depth as described mathematically in Appendix A

Abstract

The case for a new approach to the specification of pulverised-fuel ash (known as fly ash in many parts of the world) is made. The new approach is set within the context of the current Specification for Highway Works and associated Notes for Guidance (MCHW 1 and 2), such that it can be simply and rapidly incorporated into these documents. The new approach is thus proposed as changes to MCHW 1 and 2 to encourage the greater use of pulverised-fuel ash in general fill, whilst ensuring the continued construction of stable earthwork structures. Guidance on the use of pulverised-fuel ash in earthworks is also given.

Related publications

- TRL484 *Application of soil acceptability forecasts* by M G Winter. 2001 (price £25, code E)
- TRL424 *Detailed chemical analysis of lime stabilised materials* by J D McKinley, H Thomas, K Williams and J M Reid. 1999 (price £25, code E)
- TRL308 *The determination of the acceptability of selected fragmenting materials for earthworks compaction* by M G Winter. 1998 (price £25, code E)
- TRL273 *Use and application of the MCA with particular reference to glacial tills* by G D Matheson and M G Winter. 1997 (price £35, code H)
- CR353 *The use of waste materials in fill and capping layers* by P T Sherwood. 1993 (price £50, code L)
- LR686 *The use of waste and low-grade materials in road construction: 3. Pulverised fuel ash* by P T Sherwood. 1975 (price £20)
- LR48 *Settlement behind bridge abutments: The use of pulverised fuel ash in constructing the approach embankments to bridges on the Staines by-pass* by G Margason and J E Cross. 1966 (price £20)

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