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Geotechnical Specifications for Sustainable Transport Infrastructure

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ABSTRACT: The specification of the materials and methods used in earthworks and foundations for highways, railways and airfield runways can be approached in several ways. However, in part due to the sustainability agenda there is a need to use specifications that make best use of material properties, and a performance-based specification may be considered the best way to facilitate this. The advantages and disadvantages of the different specification approaches is described and discussed in this paper. The functional requirements of a performance-based specification for UK highway foundations are considered. The (recently researched) performance-based specification is explained, demonstrating the steps to its development, determination of the engineering requirements, suitable target values and the potential construction-related implications. It is shown that performance-based specifications offer the advantage of better incorporation of the principles that underpin sustainable construction but also require a fuller understanding of material behavior for their development and implementation. However, contractual issues and implications for construction need to be carefully considered to allow a full performance-based approach to be successfully adopted. It is considered in the UK that a staged implementation of a performance specification is necessary to permit the gaining of experience of both the process and the field measurement methods, some of which are relatively novel, and to reduce the risk of contractual disputes or potential failures and thus a negative reaction from the industry.

Keywords: Earthworks, Specifications, Sustainability, Field testing, Stiffness Modulus.

INTRODUCTION

It has been suggested that a 10% reduction in the cost of construction should be achievable (1) in the UK and that one of the key elements to this saving is a move to a strategy of waste minimisation and material recycling. Furthermore it has also been suggested that there is a need to ‘rethink’ the management of material resources within construction (2). For example in the UK 90% (some 260M tonnes/year) of all non-energy minerals extracted are used by the construction industry. Conversely approximately 70M tonnes/year of construction and demolition materials are disposed of to landfill. A main consumer of these materials is for the construction and maintenance of the transport infrastructure. Across the UK conservative design and planning has been identified as the prime reason for this dichotomy whereby similar materials are both consumed and discarded within the same construction projects. Additionally it is also now established that the use of primary aggregates leads to the detrimental environmental impacts of quarrying, and pollution (air, noise) from the transport of these materials to site or for disposal. The barriers to ‘sustainability’ that lead to this apparent imbalance need to be addressed, and one such barrier considered herein is the use of material specifications that do not fully utilize the material properties and the associated design of the geotechnical assets.

Appropriately designed foundations and earthworks are vital for the economic construction of overlying structural pavements (in their widest sense, such as roads, railways, airfield runways and industrial pavements etc) and the transport infrastructure in general is a vital social and economic asset that requires careful management. Earthworks and foundations perhaps present the greatest opportunity to allow the reuse of materials or to reduce the use of virgin materials as engineered fill. The most significant limitation to material reuse or reduction in quantity has been the requirement for a full understanding of the engineering behaviour of the materials involved under the applied loading – many complexities are involved – and also a lack of appropriate tools with which to measure the required parameters both in the laboratory and field.

The UK specification for earthworks and foundations has traditionally followed a ‘method’ or recipe approach to provide adequate ‘performance’, based upon large scale trials and long-term experience. However, current requirements, such as for traffic types and levels never previously envisaged, result in requirements for more innovative designs. In addition, the move to ‘design and build’ forms of construction contract, whereby short- and long-term construction risk is transferred to the constructor, also allows for more potential innovation. Partnering and other novel forms of contract also permit traditional approaches to be enhanced with a greater element of ‘value engineering’ and ‘whole-life cost benefit approach’ wherein greater performance evaluation and ‘fit for purpose’ criteria may allow more progressive design and/or the use of more recycled/marginal materials. In many cases, however, the required knowledge of material performance, laboratory and field assessment and assessment of the potential risks involved, especially in the longer-term, has somewhat stifled the full introduction of full analytical design and performance-based criteria and thus act as a barrier to sustainable construction. It is clear that innovation relating to material performance, and the *expected* performance (which is actually measured/observed on site), requires a careful allocation of ‘risk’ in the contract form used and consideration of how this can risk apportioned between the designer/specifier, contractor/constructor and material supplier to safeguard against problems.

This paper reviews the performance required for geotechnical materials to perform adequately in trafficked infrastructure, the specification approaches available and describes and discusses the development of a performance-based specification for highway earthworks/foundations. It also briefly discusses implications for its full implementation into the construction of transport infrastructure.

FUNCTIONAL AND PERFORMANCE REQUIREMENTS OF EARTHWORKS MATERIALS

There are many properties that geotechnical materials should ideally possess if they are to be considered suitable for inclusion into engineered earthworks and transport infrastructure foundations, though these may vary somewhat between the end applications of the earthwork structure. However, the materials should have generic requirements of being:

- relatively easily handled, prepared and compacted with modern plant,
- chemically stable and non-hazardous to the environment in the long-term,
- insoluble,
- non-biodegradable,
- serviceable during the design life of the structure,
- readily available at economical prices,

The serviceability requirements for these materials are primarily concerned with their engineering behavior in relation to strength and volume stability. Therefore, once incorporated into an engineered earthwork, the materials should ideally maintain these characteristics to within suitable threshold limits for acceptability. The level of serviceability required, i.e. required performance, of any material is dependent upon several factors, and these are considered to include:

- the design life requirement (usually in years) of their proposed use,
- the environmental conditions (and changes) that occur during the in-service life of the structure (often linked geographical location and drainage efficacy),
- the loading conditions experienced during construction and in-service,
- the position of the material within the overall structure,
- the inter-relationship/ composite behaviour of the material within the structure,
- the 'risks' associated with non-performance or compliance,

It is the last point that is often balanced against the costs, and if the risks can be controlled and better predicted then a more sustainable use of materials can be fostered making the construction more economic. Consequently, performance levels can only be determined if a sufficiently robust design method exists or experience in a similar environment, against which suitable targets can be set, to enable some control of the risk.

SPECIFICATION APPROACHES

In general, the specification is either based upon a method, end-product or performance related approach, and each deals with or attributes the risks in a different way. Traditionally in the UK the risk/cost balance is conservatively managed, and is based upon experience of using the same materials for similar applications (i.e. empirical guidance and method specifications). To move specifications forward to an approach where specific targets are set and have to be measured to *prove* compliance requires both a suitable design approach and suitable measurement equipment. In the more advanced approach material characteristics required for the specific application can

then be set based upon the functional or inferred parameters (with end product or performance-based specifications) and, if required, offset against performance requirements set by the construction and serviceability constraints. Therefore, in theory, any material that fulfils these specifications' criteria may then be used in the earthwork structure. However the less robust the information used to design or specify, the more prescriptive the specification, with method or recipe approaches being the most material specific and performance approaches more behavior specific.

For sustainable construction there is a need for an 'optimisation' material selection approach, whereby an understanding of the design implications of a better or lesser performing material can be predicted and accounted for. For example, in the case of a highway scheme, a lesser performing material may be suitable but need to be constructed to a greater thickness to achieve the required performance, but weighed up with regard to transportation and balancing cut and fill at the site, and or savings available in reducing/ thinning with better but more expensive materials.

Within any approach adopted the availability, quantity, transport and cost are often the major factors governing the selection of any proposed material. However, in the UK the 'environmental quality' of a construction tender proposal is now of greater emphasis in the procurement process. Therefore, for the more sustainable approach all projects (above a certain size) should attempt to achieve a 'geotechnical materials balance' by matching the amount of on-site cut and fill negating the need to import or export materials from site. Where there is a shortfall the required volume should, ideally, be sourced locally without prejudice against lower quality materials by an unnecessarily strict material specifications (3).

From the above discussion it can be seen that the suitability and acceptability of any selected geotechnical materials are largely controlled by the framework of the contract and the specification used for the scheme. The specification constraints must thus be carefully considered and chosen to ensure that an 'adequate' result, providing a minimum level of performance, is achieved. The specification must, ideally, be easily understood by all the parties and capable of being enforced economically. The three principle approaches to the specification of engineered earthworks (4) are a method specification, an end product specification and a performance specification and these are explained and commented upon in turn below.

Method Specification

The 'method' specification approach requires a particular material, and states clearly a range of material classifications and their acceptability for different applications, to be placed and compacted in compliance with a particular and stated method. Typically, the contract documentation dictates that each compliant material should be placed within a designated moisture content range to a certain layer thickness and compacted with a given number of passes of nominated compaction plant. It is then assumed, based upon previous experience, that the performance thereafter will be adequate.

The onus is to create either a method of working such that a suitably stable platform is produced or to state which (published and accepted) standard specification is to be followed that is assumed to give a level of performance (which may or may not be measured in some way) that is fit for purpose. The simple method specification is currently the most common form of approach (particularly in the UK, 5). It is based on satisfactory past performance of (generally) good quality materials handled and compacted in a traditional way. The UK Specification (5)

was derived for roads, in-particular for heavily trafficked motorway construction, and is used extensively, often in a slightly modified form, across many areas of the construction industry as a result of a strong basis of extensive experimental research and full-scale field trials (6). Typical examples of its use include the design of local lightly trafficked roads, industrial pavements, ground bearing slabs, airport runways, railways as well as the construction of engineered fills and embankments.

The UK Specification restricted the range of acceptable materials to a limited number, tightly specified by index properties such as particle size distribution and particle strength for example, although in recent years does now permit some alternative (recycled and secondary) materials that cover a broad range such as asphalt plantings and a category for hydraulically bound materials (7). There are many advantages to using method specifications, such as the wide spread familiarity with standard proven materials and techniques. However, this is reliant on the maintained quality of the source material, its water content and the compactive effort applied (assuming layer thickness is well controlled) to achieve adequate compaction and subsequent performance. These factors have the potential to vary on site through changes in weather and variable workmanship. The impetus to reuse and recycle materials, or use secondary materials, is somewhat obstructed as their characteristics are currently not well proven and insufficient experience may lead to errors in specifying the most appropriate laying procedures (3). In addition, the materials are seen as ‘equivalent’ in that the empirical design does not distinguish between performance, only material class and hence potential savings opportunities are restricted. Thus, for conventional materials the method specification approach yields adequate results but can be considered restrictive for newer materials or designs.

The disadvantages of a method specification includes the need for materials to be classified into ‘categories’ and thereafter to be controlled in a rigorous way. The classification tests used to classify the material are heavily reliant on a good ground investigation prior to construction to set the acceptability limits for site excavated materials. These acceptability limits are based upon simple index tests which are only indirectly linked to the expected performance (e.g. abrasion tests or plasticity index). This often leads to conservatism and over-design, and often over-use of primary high quality quarried materials. In addition, for a method specification no auditable assurance of build quality is possible as no measurement of the as-constructed material layer(s) is made. When using such an approach the risk of material or method non-compliance and later in-service problems rest firmly with the designer/client and there remains little flexibility for innovation and or cost/risk control.

End Product Specification

An end product specification is used in the construction of engineered fills where relatively high performance is required against some specific criteria, but the actual performance after placement is difficult to monitor. This form of specification requires a material to be compacted into an acceptable condition which is then assessed, usually as a pass/fail criterion (4). The end product target is usually specified as a function of compacted properties (as a range of acceptable water content, dry density and/or air voids) or shear strength in the case of a cohesive soil. It demands a good understanding of variations likely in the source material usually from a suite of laboratory tests at the preconstruction stage, e.g. particle size distribution, compaction behavior with variations in water content, compactive effort and so on. The resultant performance is assessed in terms of strength/compressibility (and/or permeability in some

applications) through relationship testing (7 and 8). The specified ‘acceptability envelope’ is considered by the designer/specifier to represent a condition whereby the material should perform satisfactorily. It is a useful check for ensuring that the source material when placed is not too wet or dry, or indirectly too fine/coarse or in the case of a mixed soil an imbalance of any specific size range, and thus receives an appropriate level of compaction.

The compliance with an ‘end product’ specification requires rigorous site testing by (ideally) direct measurement of the required insitu material properties to check against the specified range. In some cases for these parameters (such as density) many alternative measurement techniques exist, and the test method’s repeatability and reproducibility may be an issue which must be factored into the specified limits. In some cases the direct measurements of the end product required is difficult and indirect methods for controlling the *suitability* of the materials can be used. These are normally based on water content / pseudo –strength characterization and give a check of acceptable workability such as the Moisture Condition Value (MCV) as applied to cohesive soils (5).

The primary advantage of the end-product specifications are that they provide some assurance that a suitable material has been worked in a suitable way and achieved what can be expected of it, in terms of some measurable characteristic against a specific target value. Thus it is a very useful part of the quality assurance procedure and may be expected to ensure the quality of workmanship is adequate, and that effects of environmental changes such as wet or cold weather can be readily determined and the work programme adjusted to suit. In addition, if subsequent problems arise at the site there is an auditable information database that should demonstrate very useful information as to the state of the material at the time of placement.

The primary limitations of an end product specification are the difficulty in setting suitable target values and whether these do in fact provide a real guarantee of suitable performance. Laboratory test results, such as density or air voids, are often used as target values for the fieldwork, but can be misleading or misinterpreted as the field conditions and plant used are usually very different to the controlled laboratory preparation methods applied to the sample specimen and the environmental conditions. The main shortcomings of laboratory based tests link to the effects of confinement and often limited particle sizes allowable in the small sample containers. In addition the constrained action of compaction by a drop hammer or vibrating ‘foot’ applied to the material under test in the laboratory in contrast to the rolling, kneading and vibrating compaction action experienced in the field lead to discrepancies in setting target values. These problems can be somewhat negated by the setting of field targets for density for example from full-scale trials (though it is still prudent to perform laboratory tests to look at the effects of variability which is uneconomic at full-scale).

The pass/fail methodology of an end-product approach does transfer risk to the constructor for achieving the desired target value. However, there are often disputes relating to the number of tests required and their location when any single test fails to achieve a specified minimum value. A pass/fail approach does not readily address the actual performance of the material, and may only be an indirect or inferred indicator of suitable *likely* performance. Density, for example, has been shown to be inadequate as a direct indicator of material performance under rolling wheel load as it does not easily correlate to the engineering parameters required for performance of a road foundation for example (9). It may be a useful indicator of the final material state, however. The sensitivity of the material/foundation

‘performance’ to a (small) change in the measured value in an end product specification is often unclear and hence the cost and value benefits cannot be controlled in an effective manner by his approach.

Performance Specification

A performance specification stipulates the way in which the earthwork, either in layers or as a whole, should act under the conditions likely to be encountered in service. As a consequence, ideally no constraints are given to the choice of materials or the amount of handling and compaction they require as long as they achieve the required (measured) performance. However, guidance may be given as to which materials might be expected to demonstrate good performance or how the performance can be enhanced (by the addition of stabilizing agents, for example). In general, the earthwork performance that is required may be constrained only by the amount of support (stiffness) that is required by the structural loads from above and the serviceability-related criteria of the structures (which can mean the highway surface, railway track, airfield runway and so on) during their life. Account of the long-term environmental constraints/changes thus also need addressing, particularly for earthworks in the control of pore water pressures through adequate drainage to ensure long-term volume stability and strength/stiffness.

The advantages of a performance specification approach from a strategic view may be considered as:

- identification of performance relationships from which appropriate performance parameters can be specified,
- allows flexibility and material source individuality for the manufacturer/supplier,
- address recycling opportunities (greater use of reclaimed, blended and marginal materials etc),
- can specify higher performance for more heavily trafficked/higher loads,
- from the client’s viewpoint it can permit a greater risk/liability to be apportioned to the constructor,

However disadvantages are considered to include:

- the need for a greater level of material understanding especially in the longer term. (Although this could however be considered an advantage as engineers can design the scheme from first principles),
- the initial need for greater frequency of testing (in the laboratory and field) for design and construction assurance,
- the need for reliable methods for assuring that the fill materials used present a low risk of contamination to comply with environmental constraints,
- the potential that this may initially result in increased tendered costs due to uncertainty, and lack of experience from constructors, (especially during the introduction phase of the specification where assessment methods may be new to the industry),
- the need for current contractual documentation and procedures to be significantly revised to permit the use of a performance framework.
- the possible need for extensive trials to gain confidence in the robustness of the specification.

These issues thus require that during initial introduction support and guidance on remediation (if a section fails the performance requirements) will be required from the

specification originator, which itself has risk and contractual implications. This approach thus transfers the onus is on the specifier to ‘understand’ the material, their behavior and limitations and thus the consequence and significance of the measured performance data. Much research work has been done on the development of a performance-based specification for use in the UK and this is described below.

DEVELOPMENT OF A PERFORMANCE RELATED SPECIFICATION FOR HIGHWAY FOUNDATIONS

The Philosophy for a Performance Specification

A performance specification aims to provide a real assurance that what is being paid for is being provided, and that material performance is fully optimised in the scheme construction (10). A performance specification can only be produced if there is a means of quantifying, by direct measurement, the performance of the as-constructed product against the design. If this is possible, then a specification for the product, and the materials from which it is made, can identify the measurable criteria. This gives the manufacturer of the product freedom in both how it is made and what it is made from, which in turn creates opportunities for innovation and/or savings (e.g. in materials, process, or time). The production process may thereby be made more efficient and economic. In the case of pavement foundation construction, there are additional environmental/sustainability benefits to be gained by widening the range of possible materials or by enabling the full use of the potential properties of the foundation materials, which may then allow benefits and savings in the design and construction of the overlying, more costly, structural layers.

The decision as to which performance parameters are required is dependent on a good understanding of both the functional requirements and the performance requirements of the material/construction. The design of the pavement foundation requires target values of these performance parameters to be defined. The target values (and hence design requirements) are different for the short-term (construction) condition than the long-term (in-service) condition. This is a result of the different loading and environmental conditions. These target values can be set based upon: theory, previous experience and/or full scale trials. Each of these has limitations and it is suggested that a combination of all three methods is probably most appropriate.

Therefore, to assess material performance within a performance-based specification, the following must be available:

- a means of measuring the design-related performance parameters of the subgrade in the laboratory for both the short-term (construction) condition and the long-term (in-service) condition,
- a method of accurately predicting environmental (water content) changes in the pavement over the long-term,
- a means of incorporating the measured parameters in the design process, i.e. a suitable analytical or semi-analytical model,
- an ability to measure the *same* parameters for the subgrade and pavement foundation layers in the field, in order to assess compliance with the design, and to facilitate the setting of suitable target values for construction which will provide assurance of the quality and performance of the final product.

Generic Physical and Environmental Loading Criteria

Within the pavement's foundation (in the wider sense), and the supporting earthwork the performance required includes the following;

- provide support for a (limited) number of construction vehicles,
- provide an adequate base for the construction of the overlying layers,
- provide adequate support to the overlying structural layers long-term,
- have sufficient chemical and physical stability,
- provide frost protection to frost susceptible subgrade soils beneath,

It is clear that the main material property variables to resist load within any performance specification are stiffness and strength. In the case of the material behavior under repeated loading the 'strength' criterion is often termed the resistance to permanent deformation and has been shown to be influenced by the individual layer and, perhaps most dominantly, the interaction of adjacent layers. The stiffness of *individual* layers, whilst important, is also dominated often by the interaction of adjacent layers. These facts must be used to establish the criteria for the selection of suitable testing equipment to measure the performance of the layers/composite structure insitu under appropriate stress conditions. Frost susceptibility may determine the minimum depth of non-frost susceptible materials above the subgrade. Chemical and physical stability is assessed by durability tests, though these are difficult to predict and thus set targets on a wholly fundamental basis and traditionally pass/fail values have been empirically derived. Durability is not considered in any detail hereafter.

Pavement Foundation and Material Behavior Under Traffic

The stress pulse generated when a vehicle wheel travels across a pavement consists of vertical and horizontal stress components with an approximately sinusoidal (double) pulse of shear stress (11). This stress pattern subjects an element within the pavement to a rotation of principal stresses. This pulse varies with the speed, load and direction of the vehicle, and becomes repetitive with the passage of more wheels. This surface load (or pressure) is dissipated through the pavement structure and hence reduces with depth. The pressure distribution is primarily affected by vehicle speed and the stiffness ratio of the layers.

A cycle of stress causes both elastic and plastic deformations (i.e. strains). There are many factors that affect the magnitude of each of these strains, and consequently the material performance in a pavement. The resistance of a material to the accumulation of plastic strains is relatively complex. Recent research (13) has indicated, however, that it may be possible to control permanent strain accumulation through adequate material strength, thus allowing some assessment from simpler strength tests.

The field behavior of stiffness and resistance to permanent deformations (rutting) of materials is in general well understood, with regard to the loads applied, material layer properties and behavior and the *interaction* of layers. This last point is significant as a relatively stable/strong granular layer that is well compacted (i.e. high relative density and good interlock) above a subgrade with a propensity to accumulate permanent strain may be compromised after many load cycles as the subgrade deformation permits dilation of the granular layer above. In addition, the stiffness ratio of two material layers affects the stress distribution caused by traffic and thus the strain distribution. The non-linearity of the soils can further exacerbate full analysis as the stiffness response of the materials is affected by the stresses imposed, and thus depends on position also. These factors are most significant in the analytical modeling of the pavement

foundation structure accurately, though is important for the effective setting of target values for the as constructed foundation.

Environmental Considerations

Changes in environmental conditions, in both the short-term and long-term, will influence material performance, especially for fine grained soils. Pavement foundation design is traditionally based on construction related loading, but it is essential to consider the effects of long-term behaviour and potential environmental changes on performance. For fine grained soils this is further complicated by the observation that the material state at the construction stage affects changes that can occur long-term, primarily due to pore water pressure equilibration due to the hysteresis effects associated with these changes, (12).

The long-term equilibrium water content value, once attained, is expected to remain relatively stable under impermeable pavements. Factors such as a lowering of the water table (due to the early installation and effectiveness of sub-surface drainage), changes to the stress history of materials (due to the removal of overburden in cuttings or additional stresses due to pavement construction), changes to the material structure (remoulding due to the construction operations), material type, temperature, humidity and rainfall may all result in changes to the material's expected equilibrium water content, and hence the mechanical performance of the material (13). Although these factors primarily affect fine-grained subgrade soils, granular capping and sub-base foundation materials can also be affected if excessively wetted during construction.

The prediction of equilibrium water content and its effect on pavement performance is difficult to establish as the soil mechanics are complex and little data exists from long-term monitoring. The simplified methods in existence (12) may be expected to be conservative. For accurate laboratory testing for design, the subgrade condition must be modelled allowing for changes in its compacted state, environmental conditions (water content) and applied loading (e.g. number of cycles of load depending on the construction operations performed), and the material location (i.e. cutting or embankment). There are four main material states that should be considered:

- undisturbed: as found in the base of cuttings or 'at grade' at the time of construction,
- remolded: re-compacted soil at the in-situ water content, as found in embankments at the time of construction or after reworking,
- samples in the two conditions above, but at their long-term equilibrium water contents after equilibration of excess pore water pressures,.

For laboratory testing, undisturbed samples may be prepared directly from the subgrade, while remoulded samples can be prepared by reconstituting a sample of the subgrade using an appropriate compaction method. To create samples that accurately represent the long-term equilibrium condition, however, requires further research.

Development of a Performance Specification Through Research

The authors have been involved in the development of a performance specification that meets the criteria defined above through three key stages of research. The first comprised carrying out field measurements of the performance parameters during live construction schemes. The second comprised the design and construction of specific full-scale foundation trials to further evaluate the test methods and their applicability. This second stage produced a 'draft' performance-based

specification. The third stage was to evaluate the draft performance based specification on real sites, similar to stage one, but it further evaluated: implications for different contract types; testing regimes and their frequency; and assessed the newly proposed design methods for prediction of adequate performance. However, whilst the new design methods appeared to be sufficiently accurate, there remains room for improvement of laboratory test methods for design – mainly in their simplification for routine use (13). Until suitable routine design related tests are available, compromises have been deemed necessary. A phased introduction into practice was proposed so that experience can be gained of the proposed test methods and data produced, both to engender confidence in the new approach and to make best use of the considerable empirical experience that has been generated over many years.

The performance-based specification produced from this research, for implementation purposes, currently accommodates two different approaches.

- A CBR based design approach, to assess the subgrade, upon which the foundation is designed for both short-term and long-term, and the field compliance testing provides assurance of performance (termed the *standard approach*). This is further described below.
- A fully analytical based design approach, wherein the traditional CBR test is replaced by a (termed the *detailed approach*) for which research is ongoing (13). The ‘as built’ foundation performance evaluation can then be linked to the whole pavement design and performance.

A Draft Performance-based Specification (Standard Approach)

The draft specification developed features three iterative stages: design to achieve target performance values, a pre-construction field trial, and compliance testing during construction.

Foundation Design

The foundation design requirements for the standard approach are similar to those in current use in the UK in that the in-service design requirement utilizes the long-term equilibrium CBR (tables exist in UK guidance). However, for the short-term design of the foundation (this being the contractor’s responsibility to ensure that the foundation can be built and provide an adequate platform for the construction of the upper structural layers) the insitu CBR, or an alternative parameter such as insitu stiffness, can be utilized. The design thickness of the foundation layers is based on static linear elastic theory and comprises a step to determine the required layer thickness to provide a stiff foundation and a further step to determine the required layer thickness to prevent rutting in the subgrade from construction traffic. The thicker of the two is selected.

Target values for compliance testing during construction

To ensure that the subgrade properties found in the field are as good as, or better than, those assumed in the design CBR measurements (or stiffness) are made in the field at regular (50m) intervals and must at least match the long-term design value (the short-term design being the contractor’s responsibility).

For the next layer, the capping which is a subgrade improvement layer often utilized in the UK, a target composite stiffness of 50MPa (measured at 10m intervals in each lane with a 300mm-diameter bearing plate and contact stress of 100kPa) is proposed to facilitate adequate compaction of the sub-base above. The methods of measurement of stiffness in the field are detailed elsewhere (14), and utilizes lightweight portable deflectometer technology. The dry density after compaction should be at least 95% of the laboratory derived maximum dry density

to guard against any further reductions in air voids (measured at 50m intervals). A limit on surface rutting of any construction trafficked sections was stipulated as 40 to 50mm to protect the subgrade once covered, based on observations that approximately 50% of the rut is transferred to the subgrade (9). For the sub-base above similar limits were proposed with a composite stiffness of 65MPa. Currently the draft specification described herein is being updated based on other foundation research project (8) to permit different foundation classes to come into existence, similar to French and German specifications.

Field trial

To demonstrate that the selected materials and designs are adequate, a site trial is required (especially for larger schemes) prior to construction using the proposed materials and methods on a *representative* section of subgrade. A complete programme of in situ testing on the subgrade, capping and sub-base is required to validate the design data and target values and approve the materials. The trial section may then be trafficked, its relevancy depending on the construction method proposed, and any adjustment to the specified rut limits may subsequently be agreed on a site-specific basis. At this stage the contractor can consider different thickness of the foundation layers and combinations of materials to optimise the design. The water susceptibility of materials can be assessed by saturation of sections and further assessment to examine the possible effects of poor weather/drainage during construction. If the trial proves unsuccessful, the design/materials must be re-evaluated and a further trial carried out to confirm the design and the specification target values.

Construction Testing Regime

The subgrade is to be tested *in situ* immediately prior to capping placement to check that it meets the design values for the long term. However, if the parameters measured on the subgrade lie below the long-term design values (or any other pre-determined values which suggest that the equilibrium values may subsequently fall below the design values), then the long-term design may need to be amended as construction takes place. ‘Soft spots’ will need to be isolated and treated accordingly. If the targets for the subgrade fall below the short-term requirements for site construction (this is the contractor’s responsibility, and thus the contractor must balance the construction costs versus risks for these situations), then either additional excavation and addition/thickening of capping or subgrade stabilisation may be needed. Future possibilities include taking account of improvements in the long-term design and reduction in thickness of the sub-base, or even upper pavement layers.

Once the subgrade is shown to be acceptable, the capping and sub-base layers can be constructed. The amount of surface rutting under construction trafficking should be monitored as construction works proceed and compared to the limiting values. Capping density should be checked to guard against long-term deformation, and the top of capping composite stiffness measured immediately prior to sub-base construction to ensure that adequate compaction of the sub-base can be achieved, similarly on the sub-base layer.

Implications of Performance Related Specifications

It is considered that the proposed change in the UK to a performance-based specification for road foundations will, in the short-term, not significantly affect the use of traditional materials, but will open up new possibilities for other materials. The new specification will allow contractors to use a wider range of materials, if their performance can be demonstrated to be acceptable. The most significant change will be that materials provided will have to be shown to be able to

perform *in situ*, i.e. that the materials can be trafficked (as per the site requirements) without excessive rutting and that a target stiffness (and density) can be achieved when compacted onto a typical subgrade. Therefore a greater appreciation of the likely performance of supplied aggregates will be needed from their suppliers and contractors in general.

In the medium-term it is anticipated that the material suppliers will be required to provide performance data relating not only to the durability of their materials but also the performance parameters of stiffness and strength/permanent deformation. Similarly, constructors will be required to provide assurance of any proposed material's suitability and performance once placed.

In the longer-term, the move towards a fully analytical approach to pavement foundation design will require a much greater understanding of both the performance of the materials supplied and the use of appropriate performance test methods. In addition, the performance of stabilised materials has to date been investigated to a lesser extent than unbound foundation materials, requiring further research.

A performance-based specification transfers the risk (or liability for failure to comply with the specification) to the contractor/constructor. This is an important factor for the client/employer who may have traditionally carried much of the risk of poor performance – especially for method specifications. The specifier, however, needs to ensure that the performance criteria are appropriate and are neither too optimistic nor too conservative as to force over-design. Compliance with a performance specification is ideally carried out during the construction phase of the scheme, but may only be truly validated by monitoring the performance and properties of the structure and materials used over their design life. In many cases this is the reason for a lack of use of performance specifications in the earthworks/foundation, or from a lack of experience of performance assessment techniques. Currently, performance monitoring may only give an indication of the short-term performance of the earthwork/structure from assessing the 'as-constructed' fill. This approach, however, is gaining credence within the UK highways industry, as it allows the contractor innovation and flexibility in terms of materials and construction methods and a form of auditing of the as built quality, and the embracing of more 'sustainable' practice – at least in philosophy.

Other Applications

The development of a performance based specification for highway foundations can be transferred into other similar applications relating to transport infrastructure. Its role in encouraging better material understanding and more analytically based design is considered to be very valuable within the realms of a sustainability cultures and the pressing need to extend designs beyond that supported by experience, e.g. increasing load magnitude and cycles (i.e. design life) required for longer life roads, airfields and railways (with lower maintenance intervention).

CONCLUSIONS

The sustainability agenda dictates that better use of fill materials is made, including waste and recycled materials. It has been suggested that better decision making and economies can be afforded with regard to material use through a strategy which considers the way materials perform and hence are specified for construction.

This paper has reviewed the three types of material specification, (namely method, end product and performance). The advantages and disadvantages of each method have been considered, with regard to the best use of materials and the contractual implications. It is concluded that a performance-based approach best fits with the sustainability agenda.

Although each type of material specification has its place, and it is clear that performance specifications require a more arduous understanding of the material role and required performance to fully utilise its potential (and avoid potential problems).

The philosophy of a performance-based specifications has been explained, together with some details for a road foundation based on recent UK based research. The performance parameters required are stiffness, and strength and they can be suitably measured in the field. Density is also considered to be important to safeguard against poor materials/workmanship.

The implications of a performance approach shows the need for good communication between the contractual parties involved, the possible benefits of risk sharing and the real benefits in design optimisation that are possible.

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