Utilisation of aggregate materials in road construction and bulk fill

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Abstract
In the UK, at present, the majority of aggregate materials, for all construction applications, are obtained from primary resources such as crushed rock and sand and gravel. Material extraction results in many adverse environmental impacts and utilisation consumes a finite natural resource. In the UK we also produce large quantities of waste and by-product materials, from industrial and domestic activities, that require management or disposal. To maintain levels of development and construction but reduce the utilisation of primary aggregates, two principal options are available: optimise the use of primary materials or utilise alternative materials. This paper summarises ongoing research at the University of Nottingham, UK, which addresses both of these issues for aggregates used in road construction and bulk fill. Predictions of the in-situ performance of alternative and conventional aggregate materials have been investigated as regards both mechanical and environmental loading. Performance based mechanical specifications have been developed using a repeated load triaxial test and indirect tensile test for assessing untreated and treated materials. For the investigation of environmental performance, a tank-leaching test and lysimeter trials have been utilised. In addition, the CoURAgE project (a European-wide research collaboration, centred at Nottingham) has investigated possibilities for optimising the use of aggregate materials in the unbound layers of roads. Aspects of that project cover the importance of good design and construction techniques and, thus, are also focused on minimising the required quantity of natural aggregate material.

Keywords
Road construction, aggregates, waste materials, mechanical properties, environmental properties, optimisation.

1. Introduction
Aggregates are the bulk material used for all construction tasks (including structures and infrastructure) and are essential to the development of a modern economy. In the UK, at present, the majority of aggregate materials are obtained from primary rock and sand and gravel resources. In 1998, the total production of primary aggregates in the UK was about 210 million tonnes (Mt) [1] with approximately a third being used in road construction and maintenance [2]. A recent study [3], has revealed that across Europe an estimated 750 Mt/yr are consumed in the unbound layers of roads - which might suggest a total annual consumption of aggregates by roads of around 1 billion tonnes in Europe.

Aggregates are generally extracted from the ground via quarrying operations. Quarrying causes many adverse environmental impacts such as noise, dust, traffic, visual intrusion, loss of amenity, damage to biodiversity and the generation of derelict land [4].

Development needs to take place in a way which protects and, where possible, enhances the environment, in order to achieve sustainability. In the UK industrial and domestic activities generate in excess of 200Mt of waste and by-product materials each year that require management and/or disposal [5]. In addition, further stockpiles of such wastes are estimated in the region of 4,500 Mt [6], although much of this has been returned to beneficial uses. Examples of such materials include power station ashes, blastfurnace and steel slags, minestone, slate waste, china clay sand, municipal solid waste incinerator ashes and foundry sands. Many of these materials could be used as a substitute for primary aggregate materials in various applications and have been successfully applied to low specification applications in road construction and bulk fill. Some materials, such as air-cooled blastfurnace slag and pulverized-fuel ash can conform to higher specifications and guidance on the use of these materials has been published in British Standard specifications [7, 8]. The use of these alternative aggregate materials as a substitute for primary materials results in multiple environmental benefits including:

- a reduction in primary quarrying activity (reduced noise, dust and land consumption);
- a reduction in development of new waste stockpiles and re-use of material in existing piles;
- clearance and reduction of derelict land generated through waste disposal;
- economical disposal or recycling of marginal materials and,
- a reduction in the utilisation of finite natural resources [9].

In October 1996 the UK government introduced a tax on all waste going to landfill. The Landfill Tax was set at two rates: A lower rate of £2 per tonne (/t) for inactive (or inert) wastes and a standard rate of £7/t (currently £11/t and rising to £15/t by 2004) for all other taxable wastes [10]. The Landfill Tax has increased the cost of disposing of industrial waste materials, thereby making reuse and recycling potentially more economically viable. A similar economic incentive may be provided by the Aggregates Levy, which is to be introduced in April 2002 at £1.60 per tonne of aggregate. This levy has been designed to reflect the true social and environmental costs associated with material extraction. The resultant increase in the price of primary aggregates may encourage the use of recycled or alternative sources of materials (although concerns have been raised about material exemptions) [11].

Over the past decade, research at the University of Nottingham has been investigating how the consumption of primary aggregate material for road construction and bulk fill applications can be minimised [12, 13]. Research has focused on assessing the suitability of reused and recycled alternative aggregate materials as a substitute for primary materials. This research has investigated both mechanical and environmental hindrances, and some of this work is reported here. Minimising the use of all resources in this application has also been addressed through research into good design and construction practice [3].

2. The road construction

Roads are typically constructed from layers of compacted materials which generally increase in quality through the pavement layers to the road surface (Figure 1). The surface
layer is usually asphalt (aggregate with bitumen binder), although concrete has been widely used in the past. The subsurface layers, of which there are usually two, are made up from compacted aggregate. The materials used in each layer of the pavement are subject to specifications (Highways Agency in the UK [14]). Traditionally, these specifications cover many properties of the material including, for example, grading, particle strength and resistance to frost. The specifications generally become increasingly stringent for the higher quality materials used in the upper pavement layers, which are designed to support high, localised loading (which is dispersed through the layers). The upper layers are also subject to greater influence from other external factors such as temperature and associated maintenance.

3. Alternative aggregate materials

Given the intensity of loading to be experienced by the pavement surface, it follows that alternative aggregates are most likely to find use in the lower layers of pavements. In this role their consumption will be high (due to the volume of material in such layers), but absolute strength will be less important than a good stiffness in spreading traffic loading efficiently to the underlying subgrade soil. Conventional test procedures typically describe properties of the aggregate which are then compared to those of an adequately performing material. It is then concluded whether the candidate material is suitable. Such an approach is often inappropriate for the assessment of alternative aggregate materials because the material properties (e.g. particle sizes, grading and chemical structure) differ substantially from those of traditional materials. A more appropriate method of material assessment (for both conventional and alternative materials) is to simulate the in-situ loading (both physical and environmental) and to determine whether the measured response is adequate for the purpose. This is the approach that has been taken at the University of Nottingham.

4. Mechanical performance procedure

Table 1 provides a list of the materials tested at the University of Nottingham in a series of projects which concentrated on the mechanical properties of alternative materials. To determine the real response of these materials to pavement loading, it was quickly ascertained that a performance-related testing strategy was required. The chief element of the programme adopted was the repeated load triaxial test (RLT). This equipment is illustrated in Figure 2. A cylindrical sample of compacted material (150mm diameter, 300mm high) is confined within a pressure vessel which simulates the support from surrounding material as experienced in the road construction. A repeated axial stress is applied to the top face of the specimen (sometimes the lateral stress is also cycled) to simulate the repeated passage of loaded vehicle wheels over the material in question.

Using this equipment it is possible to determine the stiffness of the specimen (which can be related to the load spreading quality of the material) and the resistance of the specimen to the incremental build-up of plastic strain over many thousands of cycles (which is seen in the completed pavement as rutting). By this means, it was quickly demonstrated that there are some alternative aggregates which have comparable performance to those of their conventional brethren. Slate waste is an example of such a material. Its stiffness and permanent deformation characteristics are broadly similar to those of, say, crushed limestone although the material exhibits some unusual features due to its flaky nature which may necessitates particular action on site (for example compaction with a mesh roller rather than a more conventional drum roller).
However, when the mechanical quality of the aggregate is lower than that of conventionally employed materials, stabilisation may be an option to remedy performance. Nunes [9] conducted trials on many candidate alternative materials, and used conventional and alternative binders, including cement, cement kiln dust, flue-gas desulphurisation gypsum, pulverized-fuel ash, granulated blast furnace slag and lime, to stabilise them. By compacting the materials into 150mm diameter, 70mm high cylinders, an indirect tensile (“Brazilian splitting”) test could be performed (Figure 3). Such testing is preferred to that of cube crushing as the loading on pavements is almost always insufficient to cause compression failure but is sufficient to, and frequently does, cause cracking of pavement materials due to fatigue or other tensile reasons. Some typical results are shown in Figure 4 for pulverized-fuel ash stabilised with cement. It can be seen that:

- the strength of the mixture increases with the amount of binder,
- the strength of the mixture increases with time since production, and this strength gain continues for several months (or longer for some mixtures).

Because Nunes tested a large number of different mixes he was able to show that the stiffness and strength properties were functions of the particle size of the coarse fraction of the mixes, and also of the amount of binder. Figure 5 shows, for materials tested in the indirect tensile apparatus 90 days after fabrication, that there are three distinct groupings. Those mixtures having only fine components (e.g. pulverized-fuel ash) are considerably less stiff than materials having medium-sized components (e.g. china clay sand) which are again less stiff than materials having coarse components (e.g. blastfurnace slag). Those mixtures exhibiting higher strength generally have more, or a more efficient binder, thus demonstrating that the addition of binder always has a great effect on strength but its effect on stiffness depends on the coarsest particle size.

The implication to be drawn, is that it will generally be more cost effective to treat alternative materials with a coarse particle size (such as many slags, bottom ashes and marginal, conventional aggregates), then to treat fine industrial residues. This is partly because of the amount of binder required to develop the same stiffness, and partly because high stiffness is more important to pavement performance than high strength. This is certainly the case for the lower layers of the pavement structure where load spreading is the key requirement rather than the prevention of cracking. Fine-grained alternative materials are more likely to have a role as constituent materials in the binders.

It is also apparent that accepted practice in road pavement design may need to change to use alternative materials and marginal aggregates optimally. The treated alternative materials (Figure 5) exhibit stiffness well in excess of those found in conventional unbound granular materials (UGM). Thus, in principle, layers comprising these materials need not be as thick as layers of the UGMs which they replaced. However, they are susceptible to cracking, which the UGMs were not. Thus consideration must be given to providing a strain absorbing layer immediately above them in order that the cracks forming in the lower layers do not cause reflection in the higher layers. Alternatively, a high-quality conventional bound material, thicker than normal, might be placed immediately above marginal quality aggregates thereby providing an adequately performing pavement.
5. Environmental assessment procedure

Many conventional and alternative aggregates and mixtures have been shown to possess suitable mechanical performance criteria for use in road construction applications. However, the use of such materials has come under scrutiny by environmental protection organisations (such as the Environment Agency in England and Wales) because of the non-conventional source of such materials. Although the use of alternative aggregates holds many environmental benefits to society, concerns have been raised over the potential of such materials to contaminate ground and surface water systems. Some alternative aggregates, inherently or as a consequence of the process from which they are sourced, may contain environmentally undesirable elements or compounds, such as heavy metals or organic species [15]. It is therefore necessary to demonstrate that no, or an acceptably low, risk of contamination to the environment would result from usage of aggregate materials in road construction.

The UK Ground Water Regulations introduced in 1998 [16] suggest very strict limits for discharges of substances to groundwater. This legislation may require the road construction industry to perform environmental risk assessments for the use of any alternative or conventional construction material, in order to be able to demonstrate an acceptably low risk. This legislation does not however specify the absolute quantity or concentration of contamination that may be discharged into groundwater. In England and Wales, discharge consents are currently granted by the Environment Agency, on a site-specific basis, depending upon the in-situ hydrogeology and groundwater quality. The nature of this assessment hinders the use of alternative aggregates because of the cost and time consuming nature of the approval process. This is especially important as the constituent material is usually the constructor’s choice made only a few days or weeks before application.

A study carried out for CIRIA [15], used index leaching tests on untreated materials to assess contaminant availability. The results appeared to be unduly pessimistic and unrealistic for the road construction situation since they did not replicate;

1. the real gradings of most alternative materials and their compaction when used in a road construction,
2. the in-situ hydraulic regime (which is, normally, only partially saturated),
3. the combination with other aggregates or binders, required for mechanical reasons, which may dilute or amend leachable levels, alter the pH (and, hence, the solubility of leachable components) and reduce the permeability (thereby hindering the ingress and egress of water to the road).

Taking a similar approach to that used for developing the performance-based mechanical specifications, an environmental assessment procedure was developed to address the influence on leaching of the in-situ material conditions described above. The environmental assessment strategy is summarised below and the materials tested in the programme are listed in Table 1.

1) Material Characterisation. The solid composition of each material was determined using X-ray fluorescence spectrometry. This data gave some information about the materials and an indication of what contaminants may be of concern. However, if a certain element or compound is present in a material it cannot be concluded that all or any of it will leach out under real conditions. It was therefore necessary to carry out leaching tests on the materials. Rapid leaching characterisation was carried out using the draft CEN standard PrEN 12457 “Compliance test for leaching of granular wastes
and sludges” [17]. This test was chosen, principally, because it is being developed as a European standard and also because the test material determines the pH of the leachant (which reflects the road situation being modelled). The test conditions are significantly harsher than the in-situ environment and should result in the release of the majority of the leachable components.

2) **Effect of material particle size on diffusive leaching.** The leachability of intact (real grading) material was carried out in a tank-leaching test. The single batch, non-agitated, leaching test procedure was adapted from two existing tank-leaching tests [18, 19]. A 2kg material sample was placed in a tank with distilled water at a liquid to solid mass ratio of 10 (Figure 6). Samples were taken for analysis at periods over 64 days.

3) **Effect of material compaction on diffusive leaching.** Leaching from compacted materials was assessed using the tank-leaching test described in step 2. Compacted, cylindrical (150mm diameter, 70mm high) material samples were prepared and cured for 90 days to enable any binding reactions to become effective. The tests were carried out at a liquid to solid volume ratio of 10. The volumetric ratio accounts for variations in material density (e.g. slag and ash) which, in the field, would result in different material masses being required to perform the same filling task (e.g. a pavement layer thickness).

4) **Assessment of binder treatments.** Conventional and alternative binders and mixtures were tested using the procedure described in steps 1 to 3 above. The binders and binder activators used included a bitumen binder in addition to those used by Nunes [9], which were listed earlier.

5) **Full scale lysimeter trials.** The lysimeter field at the University of Nottingham consists of nine individual test cells. Each cell contains compacted aggregates or mixtures with a surface area of 1m² and a depth of 0.35m. The cells are exposed to natural environmental conditions and any percolating precipitation is collected and analysed.

The effects of the physical variables (grading, compaction, binder treatment) were investigated by comparison between consecutive stages of the laboratory procedure. The lysimeter trials were used as a tool to relate the laboratory testing to the in-situ conditions.

A typical set of tank-leaching test data is illustrated in Figure 7 [20]. The graphs show the leaching of calcium and boron in tank-leaching tests on the full graded material, compacted material and the material treated with an alkali binder. The graphs illustrate how compaction slows down the leaching process and how the addition of an alkali binder reduces the leaching of the boron but increases the leaching of the calcium because of its presence in the binder.

In general, the environmental assessment programme showed that:

- The total amount and rate of leaching is affected by the material condition (i.e. grading, compaction, binding) but cannot be determined from the solid composition of the material. In general, larger particles leach at a slower rate than finer particles and compacted materials leach slower than uncompacted materials (but this is most significant for the materials with the lowest permeability when compacted).

- Leaching may however be more significantly controlled by the pH of the leaching environment. Any prediction of leaching potential should therefore include a robust prediction of likely pH. A tank-leaching test may be the most suitable technique for such an assessment based upon the data obtained from the lysimeter trials.
• Most binder treatments significantly modify the leaching behaviour of a material. Leaching from the mixture is controlled by the leachable species in the material and binder, when each is considered alone, but also by the physical and chemical action of the treatment on the mixture. Bitumen appears to provide a physical barrier whilst other (principally alkali) binders act by pH modification and/or, as a physical barrier, but usually at the expense of a high pH leachant rich in calcium and sodium.

It is very important to realise that the quantities of contaminant leaching from the treated materials are all very low and are therefore encouraging for the use of alternative materials. Although some of the contaminant concentrations in the leachates somewhat exceeded typical site-specific targets, these figures would only apply to emissions from the boundary of the material construction. It is very likely that significant attenuation (by mineral adsorption, precipitation, bio-fixing and similar processes) will occur extremely close to the source, thereby reducing concentrations to acceptable levels. This aspect of immediate attenuation is currently being studied [21].

6. Optimising material use

At present the reliable performance of the unbound granular material (UGM) layers of a pavement is ensured by;

a) the addition of a thicker aggregate layer than calculations based on the mean material properties would suggest and,

b) the refusal to use materials for which material behaviour has not been ascertained by experience or field trials.

Both practices are inefficient and lead to unnecessary wastage. An alternative strategy is to down-grade the UGMs and to use somewhat thicker, high performance, bituminous surfacings. This increases reliability, but only by incurring greatly increased economic and environmental costs. In order to minimise economic and material wastage, a reliable framework for the assessment of any potential UGM (natural or alternative) is required. To achieve this goal the 'CoURAgE' project [3]

a) assessed UGMs in a variety of ways to determine those test procedures which can deliver useful characterisations,

b) determined the variability of in-situ paving conditions which can have a large effect on actual UGM performance.

A programme of in-situ monitoring of UGM condition in pavements revealed that the moisture content of the UGM varies considerably with the season. In base layers (those immediately beneath the bound surfacing) the variation is between 40 and 90% of that required for best compaction. For the lower sub-bases an even greater variation between 30 and >100% of this value was measured. The in-situ monitoring also revealed that the moisture in the pavement structure was very dependent on the;

• integrity of the sealed surface,

• width and imperviousness of the shoulders of the pavement (Figure 1),

• level of the pavement (raised pavement or pavement in cutting),

• ability of the pavement to self drain (the UGMs permeability and the adequacy of the pavement's drainage system).
For laboratory assessments, the repeated load triaxial test, as described earlier (Figure 2), was found to give much more reliable indications than methods in current use. Using this test, the effects of changing moisture content were studied and it was found that significant reductions in the stiffness of the UGMs (which dictates its ability to spread traffic loads efficiently) were observed as the moisture content increased. In addition, significant increases in permanent deformation (experienced in the pavement as susceptibility to rutting) were observed as the moisture content increased. These results were confirmed by in-situ measurement of the pavement's resistance to loading which showed a very serious degradation as the moisture content of the UGM rose.

Currently, it is common European practice to determine the properties of material indices, which are often performed only on some of the large particles taken from the mixture. Thus it is recommended that more effort should be given to determining the relevant mechanical properties of the compacted aggregate mixture (the UGM). In addition, the testing programme must assess UGMs at the likely in-situ moisture contents which they will have during the life of the pavement. The moisture content variation may be expected to be large and further studies may be necessary to ensure that a reasonable estimate can be obtained. The pavement should be designed, as far as possible, to keep water out and to drain as readily as possible, thus maximising UGM performance contribution. It was estimated that European pavement construction could be saving of the order of 3.5 billion Euros per annum, taking reasonable assumptions about usage in construction and reconstruction, if appropriate steps along the lines just indicated were employed. These savings do not include the additional benefits which would result from the reduction in environmental impact if industrial residues were used so that conventional aggregate quarrying and dumping of wastes are both reduced.

7. Discussion and conclusions

Determining the mechanical properties of alternative materials using performance based specifications, indicated that many such materials performed as well as (or even better) than conventional materials. The stiffness and strength properties of the materials and mixtures were dependent on the coarsest particle size of the material and the amount of binder. Coarse materials had a higher stiffness than fine materials and also required less binder to achieve a particular strength. A repeated load triaxial test and indirect tensile test were effectively used for testing sole and treated materials respectively. To accurately determine the likely in-situ performance the material should be tested at potentially realistic moisture contents. In addition, the high strength and stiffness exhibited by many of the treated alternative aggregates may enable the thickness of pavement layers to be reduced and thus the overall consumption of materials to be reduced without any loss in performance.

The study of environmental performance illustrated that under realistic material conditions (graded, compacted) the contaminating potential was less than that which would have been estimated from using rapid bench-top tests. Under realistic assessment conditions (simulated by the tank-leaching test) many of the materials could conform to site specific leaching targets set by environmental protection agencies. Some materials (e.g. china clay sand) performed better than conventional materials and for other materials certain binder treatments could reduce the overall leaching potential. An aggregate or treated mixture should be selected to match the environment of usage in terms of both the concentration of leached constituents and, maybe more importantly, the pH of that environment. The modification of a materials pH by the addition of an alkali binder can be
very significant in reducing leaching, but the binder is likely to introduce some contaminants itself (e.g. calcium).

It is clear that many alternative aggregate materials have the potential to be used in the construction of pavement layers or as bulk fill. It is also possible to optimise the consumption of both conventional and alternative aggregate materials by spending more effort in determining local moisture and performance-related material properties. In short, it is important for the designer to consider the relative performance, economic and environmental benefits of the different designs that are now available.

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References


Fig. 1. Schematic diagram of a typical road construction cross-section (not to scale—approximate dimensions).

Fig. 2. Schematic diagram of the repeated load triaxial test apparatus (RLT).
Fig. 3. Schematic diagram of the indirect tensile test apparatus.

Fig. 4. Indirect tensile strength stabilisation curves for pulverized-fuel ash and cement mixtures [12].
Fig. 5. Relationship between stiffness modulus and tensile strength for different aggregate families and mixtures (90 day curing) [12].

Fig. 6. Schematic diagram of the equipment for the tank-leaching test (shows set up for testing material at real grading) (not to scale- approximate dimensions).
Fig. 7. Typical tank-leaching test results from a material uncompacted, compacted and treated with an alkali binder.
Table 1.

Mechanical and environmental testing.

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<th>Material</th>
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<td>Slate waste</td>
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KEY: U = Tested Uncompacted  C = Tested Compacted  T = Tested Treated