Abstract

The paper firstly describes the unique characteristics of unbound base layers. The roles performed by unbound aggregate bases are defined and this leads to a discussion of the necessary properties required to achieve these, a summary of the advantages and disadvantages of using aggregate in the base and the mechanisms at play within such layers. Reference is made to a fundamental understanding of material performance which is then applied to the means available for measuring the relevant properties of aggregates for use in bases. The paper concludes with a review of areas in which understanding is poor and draws some implications for practice.

Keywords: Pavement bases, aggregate, laboratory testing, in-situ behavior.

1. Introduction

Unbound aggregates have formed the basis of all engineered pavements since engineering began [1]. In affluent societies, asphalt and portland cement concrete has been a common replacement material for the base layer of heavily trafficked roads as these materials are stronger and stiffer and less susceptible to environmental moisture effects. However, resource conservation and economic stringency means that these solutions must be re-evaluated and, once again, the unbound base must come under scrutiny. At the same time the availability of the best quality crushed rock aggregate is becoming more scarce as extraction permits become less easy to obtain, while pressure to use replacement aggregates from wastes and recycling grows. In such
a situation there is a need to re-state our understanding of the principles of behavior and methods of use of unbound aggregates in pavement bases. This paper seeks to address these issues.

2. What is an aggregate base?

2.1. Main structural layer
The base is the chief structural element of a pavement. It is the engineered heart, and the success or failure of the pavement's role depends, above all, on the base's performance. Certainly there are other important elements of the structure - for example, the surfacing which provides a suitable interface for tires - but these other parts could not function without a base. Get the base right and the essence of a successful pavement is assured.

2.2. Unbound
The performance of any base - whether asphaltic, portland cement concrete or unbound aggregate - relies, primarily, on the interaction of the individual (mostly large) stones within the mix. This basic stone-to-stone behavior is then modified by the binding agent between the stones. In the case of an unbound aggregate base this modification is achieved by the combined influence of the finer aggregate particles and the water which rests in the pores of the mix. It is for this reason that untreated aggregates may be classed as being “hydraulically” bound.

2.3. Bulky but of cheap material
Unusually for an engineering material, aggregate is, inherently a high volume and low-cost commodity. If specifications demand a material which cannot be sourced, placed and used cheaply then the rationale for the use of aggregate is seriously diminished. Instead, asphaltic and portland cement based products become more acceptable as their higher unit cost permits closer production control. For these reasons, it should undergo minimal preparation and treatment and, if unavoidable, these processes must be fast and applicable to high volumes. This unusual situation may lead to the problem discussed in Section 4.2b.

2.4. Not directly trafficked
A further aspect of a pavement base layer is that, once installed, it is out of sight. It receives some direct trafficking during construction but, thereafter, is hidden and protected by the surfacing. Thus unacceptable performance is usually monitored indirectly as rutting or cracking appears at the surface. Observation of the causes of this distress are often difficult or impossible. Furthermore, it may be difficult to distinguish between pavement distress caused by faults in the base or in higher layers.
3. What is an aggregate base for?

In order to meet its role as the main structural layer of the pavement, the aggregate base has to perform three principal (structural) functions. Successful performance of these functions is assisted if the layer can also perform some secondary functions. Each is discussed below.

3.1. Principal functions

3.1.1. Subgrade protection (stress distribution)
The first roads were merely the tracks taken by vehicles across the natural soil. Structurally, this is only an adequate answer when the soil can carry repeated trafficking without significant deformation. In most cases rutting quickly develops because the stress on the soil exceeds some critical value [2] or approaches failure [3]. The role of the base is thus to attenuate the stress level on the subgrade soil to a level which the soil can withstand without significant deformation.

3.1.2. Support for surfacing
In addition to its duties to the layer below, the base also has to provide adequate support for the surfacing. If it fails to do so the upper pavement layers will be forced to perform a structural role for which they are not equipped. Rapid failure in the form of wearing course slippage, map cracking and surface pot-holing may result.

3.1.3. Construction platform
Although the above two functions are the primary ones of interest for the completed pavement, the aggregate base has an important function to perform during construction. The paving plant must be provided with a stable platform on which to lay the pavement's surfacing. Should this not be available the surfacing will be difficult to lay to the correct falls and eveness and adequate compaction of these upper layers may not be possible.

3.2. Secondary functions

3.2.1. Drainage
As indicated above, the performance of the aggregate which comprises the base is very susceptible to the water condition. Within limits, the dryer the base the better it will be (see Section 5.2 below). Thus a base which can also function as a drain will often perform better than one that does not. Similarly, a draining base will assist in reducing the water content of the subgrade which will, in turn, help to ensure better performance. In dry climates, or in pavements provided with a lower layer which is specifically provided to act as a drain this function will be less important.

3.2.2. Subgrade protection against frost
Uneven heave of a pavement may occur due to frost-induced swelling of susceptible soil. Aggregate which is not too rich in fines will provide an insulating layer which is not, itself,
susceptible to heave. Where frost conditions are particularly severe (e.g. Northern Central States and Canada) the insulation will be insufficient to prevent soil freezing in the Winter but will help to limit differential heave by spreading the uplift effect.

3.2.3. Subgrade protection against environmental damage
Somewhat in conflict with 3.2.1 above, aggregate bases may provide only a semi-permeable layer. If this is the case then they may act to hinder downward movement of contaminants from the surfacing layers. The provision of such an aggregate base will help to delay and diminish soil and groundwater pollution from pavement surface run-off. With the increasing pressure to use cold-mix asphaltic emulsions, the possible contamination due to chemicals leaching from pavement surfacings could also be reduced in this way.

If the semi-permeable aggregate base may be able reduce contamination, would not a fully impermeable asphaltic or portland cement concrete base perform better? The disadvantage of using these materials is that the base would be thinner and liable to cracking. Thus contamination might be relatively high in concentrated locations. Furthermore, when limestone or other alkaline aggregate is used for the base, the pore water chemistry will not be conducive to the transport in solution of many of the more common contaminants.

3.2.4. Waste disposal
While pavement engineers can see the possibilities of the aggregate base to act as a break on pollutant migration, politicians appear more interested in its potential for consuming a wide range of waste and by-product (‘secondary’) materials. This is an imposed and artificial role for the pavement. It reverses the requirement from a pavement-needing-an-aggregate to an aggregate-needing-a-pavement. It may be sensible from a wider environmental perspective but can introduce pollutants into the layer which could be acting as a break to groundwater contamination. Mechanically, many ‘secondary’ aggregates are less competent than primary aggregates. This is not an inherent disadvantage providing the attitude described at the end of Section 4.2 item 2 is adopted.

4. Why use aggregate?

4.1. Advantages
The advantages of using aggregate as the base material may be summarised as follows.
1] It is cheap to obtain and use, although the price of the best quality material will often be sensitive to transport costs.
2] In most localities aggregate is readily available, although supplies in metropolitan areas may have to be hauled from outside the area because of the difficulties of obtaining quarrying permission close to residential zones.
3] Aggregate is usually simple to place and compact. Provided moisture levels are controlled within reasonable limits, few aggregates will experience serious segregation. Vibrating rollers provide a simple and widely available means of preparing aggregate for use in the pavement.
Together with graders these are the most complex machinery which is required. This situation may be compared positively to that of asphalt and portland cement concrete.

4] Aggregate is a very tolerant material being insensitive to misuse. Inadequate compaction or segregation will not cause immediate failure of a pavement base, even though some reduction in performance will result.

4.2. Disadvantages
Some of the disadvantages of using aggregate to form the base are as follows.

1] The necessity of using a minimally treated material means that it is impossible to engineer it to meet all requirements equally well.

2] It may be argued that the chief disadvantage facing aggregates for use in bases is not technical but one of image. A frequent consequence of the minimum intervention/cost strategy is that users consider aggregate properties to be unimportant - somehow assuming that cheapness of purchase can be associated with a cavalier attitude to use. Users often believe that all aggregates will perform the same, even though their geologic, particle shape and moisture characteristics may differ widely. Specifications may reinforce this assumption by only making reference to ‘recipes’ and particle properties and never to layer properties. Additionally, such specifications hinder innovation by insisting on historically acceptable materials rather than on some measurement of adequate performance.

Unfortunately, as a result, aggregate base failures have been all too frequent. Where users are aware of the problems, the tendency has often been to increasingly constrain the limits for acceptable material. Specifications have become tighter and tighter and are in some danger of undermining the very reason for using aggregate in the base. To ensure a successfully performing base, the real solution is not to adopt ever-tightening restrictions but to permit a wider range of materials and then to carefully characterise the available material so that it can be used optimally in the pavement.

5. How does it work?

5.1. Macroscopic
At the macroscopic scale aggregate performs by being stiff, resistant to permanent deformation and having a balanced value of permeability. Each of these is discussed, briefly, in turn.

5.1.1. Stiffness
The stiffness, or resilient modulus, of the aggregate layer is the chief mechanism by which the layer spreads load down from the high localised stresses imposed by vehicle tires to the level which the subgrade can tolerate without undergoing excessive deformation. Strictly, it is the modular ratio which controls load spreading. If the modular ratio of base stiffness to the stiffness of the underlying layers is high then load spreading will be efficient. However, the drawback of a
high relative stiffness is a high stress gradient within the base which imposes a greater requirement for resistance to permanent deformation on the aggregate itself.

5.1.2. Resistance to permanent deformation
Only the very weakest aggregate undergoes noticeable, irrecoverable damage in one loading application. Thus strength is seldom of direct interest. Instead the incremental build up of the tiny irrecoverable deformations which occur under each cycle of loading is the subject of concern. In many aggregates the initially high rate of development of deformation will quickly slow, perhaps even halting. In other aggregate bases deformation will continue, and perhaps even accelerate (Fig. 1). The former behavior is required of a successful base.

![Figure 1 Possible Permanent Deformation Behavior of an Aggregate Base](image)

5.1.3. Permeable or Impermeable
In Section 3.2.1 the desirability of drainage was described. This will require a permeable aggregate which, in turn, implies the need for an open pore structure. However drainage not only requires a permeable pore structure but also that those pores are full of water and that the layer has somewhere to drain to. Air in the pores will seriously limit the ability of the aggregate to drain even if the aggregate is open-graded (for this reason laboratory determined values of permeability are unlikely to be representative of base layers in-situ). Similarly, if the outlet drain to which the base is connected is blocked or has inadequate falls, drainage will not take place and the base will act more as a bathtub [4].

Where the aggregate is to behave as an attenuating barrier to water flow (Section 3.2.3) then the pore air is likely to be an important element in slowing down flow.
5.2. Microscopic

The desired behavior of aggregates for base layers derives from the arrangements of the individual aggregate particles one with another. Particle roughness and particle micro-texture each have an important influence on the mechanical behavior of the aggregate. Thom & Brown [5] showed that resilient modulus was largely a function of stone surface friction (micro-texture) and that the resistance to the build up of permanent deformation largely a function of the roughness of individual particles. The explanation for this control of behavior by the micro-texture and particle roughness is likely to be complex but would include an assessment of the behavior of the points at which stones touch. Here there may be rolling, slippage and wearing of the asperities of the stones. Whole particle breakage is unlikely in a graded mix because of the support offered by the surrounding particles. There may be some under direct roller compaction contact at the surface but even this appears to be of minor importance (Fig. 2) [6].

![Figure 2](image)

**Figure 2**  Damage of an ash aggregate during compaction [6]

Perhaps because of the importance of particle contacts and because the area of these contacts is likely to be controlled by the stress acting across them, the resilient modulus and permanent deformation behavior are found to be non-constant, varying with the applied stress level. As the stress increases, so stiffness and resistance to permanent deformation increase. In common with all geotechnical material, it is not the absolute stresses which are critical but the effective stress level (the difference between the applied stress and the pore water pressure). It is for this reason that drainage is important. For the same reason some pore water along with air is beneficial as pore suctions will develop, increasing the effective stress and hence both stiffness and resistance to permanent deformation (Fig. 3 and Table 1) [7,8].


Packing also has a major influence. It will be controlled both by the grading and by the density. Figures 4 and 5 [9] show that, based on the results of laboratory repeated load triaxial tests, a somewhat open-grading improves the stiffness (typical crusher run aggregates plotting towards the left of the figure) while density has little effect. Resistance to permanent deformation is very sensitive to density but insensitive to grading (except at very low compactions). [In Figures 4 and 5, n is defined such that

\[
\% \text{ finer than particle size } d = 100\left(\frac{d}{D}\right)^n
\]

where D is the maximum particle size.]

![Figure 3 Stiffness variation with Moisture Content][7]

5.3. Conflict between functional requirements
These findings, together with the desire to improve drainage suggest that a cautious move towards mixes with less fines would be beneficial. Within limits there does not appear to be a conflict between the need for improved drainage and improved mechanical performance. However, as other papers to this Symposium report, use of more open-graded aggregate can lead to excess fines in the production phase. Thus a rational method is required to enable a comparison of improved performance with increased production costs.
6. Implications for tradition

The foregoing summary of our understanding of the behavior of unbound aggregates has a number of implications for designers and constructors of aggregate bases. Mechanical performance has been seen to rely on the resilient modulus and permanent deformation behavior of the aggregate - factors influenced principally by moisture and density condition.

Figure 4  Sensitivity of stiffness to density and grading [9]

Table 1  Sensitivity of Aggregate Performance to Moisture Content [8]
<table>
<thead>
<tr>
<th>Aggregate</th>
<th>Moisture content (%)</th>
<th>Stiffness (MPa)</th>
<th>Assymptotic Permanent Deformation Strain (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Limestone</td>
<td>1.86</td>
<td>1071</td>
<td>2040</td>
</tr>
<tr>
<td></td>
<td>2.29</td>
<td>1558</td>
<td>3160</td>
</tr>
<tr>
<td></td>
<td>3.15</td>
<td>830</td>
<td>48210</td>
</tr>
<tr>
<td></td>
<td>3.38</td>
<td>747</td>
<td>35240</td>
</tr>
<tr>
<td>Soft Limestone</td>
<td>3.09</td>
<td>1415</td>
<td>2840</td>
</tr>
<tr>
<td></td>
<td>3.51</td>
<td>1350</td>
<td>1460</td>
</tr>
<tr>
<td></td>
<td>4.33</td>
<td>429</td>
<td>7860</td>
</tr>
<tr>
<td></td>
<td>4.42</td>
<td>393</td>
<td>6030</td>
</tr>
<tr>
<td></td>
<td>4.72</td>
<td>333</td>
<td>26690</td>
</tr>
<tr>
<td>Fine Grained Granite</td>
<td>3.21</td>
<td>416</td>
<td>5440</td>
</tr>
<tr>
<td></td>
<td>3.50</td>
<td>338</td>
<td>3580</td>
</tr>
<tr>
<td></td>
<td>3.65</td>
<td>345</td>
<td>4470</td>
</tr>
<tr>
<td></td>
<td>4.17</td>
<td>299</td>
<td>6880</td>
</tr>
<tr>
<td></td>
<td>4.64</td>
<td>301</td>
<td>11150</td>
</tr>
</tbody>
</table>

* i.e. assymptote of 'Stable' result in Figure 1
From these observations the following statements may be derived.
1] Mass strength is a largely inappropriate means of describing the aggregate as it refers to behavior under single and excess, not repeated and sub-failure, loading.
2] Particle strength is a largely inappropriate means of describing the aggregate as particles do not crush significantly even when they are weak and under direct compaction.
3] Pavement performance will be partly controlled by the degree of non-linearity in the aggregate. At the top of the base layer the stress levels due to trafficking will be much greater than at the base, so a rational design must take into account the changing moduli and resistance to permanent deformation across the base layer.
4] The grading distribution of the aggregate in the base is of secondary importance, but a more open grading is usually to be preferred for both mechanical and hydraulic reasons.
5] An engineered design is unlikely to find one aggregate to perform all the required functions equally well. Thus selected sub-layers could be included within bases to meet individual requirements.

![Figure 5](image)

Figure 5  Sensitivity of permanent deformation to density and grading [9]

6] Weaker aggregates may be used, provided that their stiffness and permanent deformation properties are known and that they are then used in an appropriate manner. This might involve the treatment of the aggregate by a light binder (cement, lime, ash, slag or gypsum in some combination) or demoting the material to a slightly less honorous role in the pavement (see Section 9).
7] ‘Secondary’ aggregates should be assessed on their merits by relating their behavior to those performance measures of interest, not to traditional requirements. The chief hindrance to their use is more likely to be environmental rather than mechanical.

From this perspective it will be apparent that a candidate material for an aggregate base must be assessed against its mechanical and hydraulic requirements. This requires a new approach to testing, the principles of which are outlined in the next section.

7. How can we be sure it will work?

7.1. Principles of assessment

Initial assessment of an aggregate is almost certain to take place in a laboratory. While there are certain advantages in undertaking a trial pavement construction this can seldom be performed enough in advance of the final construction works to allow design adjustments or material re-selection to be made. Thus it will be necessary to replicate in the laboratory, as far as reasonably possible, the conditions of the pavement base. This will require:

1] a similarity of stress magnitude & régime (repeated loading of the correct period).
2] a similarity of grading & packing (density and grading should be representative of the as-placed material). This, in turn, will require large specimens to prevent undue specimen : particle interaction problems.
3] the measurement of relevant properties (resilient modulus, permanent deformation resistance and permeability).
4] the collection of results which can later be compared with relevant in-situ end-performance testing (thus enabling appropriate compliance procedures).
5] tests which are practical to carry out in routine testing laboratories and which give repeatable results.
6] that costs are not excessive.

7.2. Laboratory assessment

While researchers are not yet fully agreed about all of the details of the laboratory tests which would meet these principles, it seems clear that the following four types of tests are needed (although not all will apply in all climatic zones).

- Triaxial - a repeated load test with recording of both resilient and permanent deformation characteristics.
- Permeability - a 'trough' test with low hydraulic gradients to model sub-horizontal drainage layer behavior. Figure 6 gives an example [10].
- Soundness - tests to evaluate the stability of the aggregate to environmental attack. This may include susceptibility to damage by wetting and drying, by freeze-thaw or by other physio-chemical processes.
- Frost Heave - a simulative test in which the tendency for ice wedging is assessed.
7.3. **In-situ assessment**

Agreement on in-situ performance testing is at a less advanced stage than for laboratory tests. Testing either aims to measure in-situ performance for contract compliance or for assessment purposes (or both). The choice and design of an in-situ test may vary accordingly. An additional complication is that an in-situ test will generally measure a response which is influenced not only by the properties of the base but also by the underlying layers. At present it is only practicable to assess the mechanical and hydraulic properties, perhaps using the following apparatuses.

- **Static Plate** - Stiffness may be estimated by looking at the load-deflection response of an incrementally loaded plate. Unfortunately it is impossible to separate permanent and resilient elements of response.
- **Repeated Plate** - By releasing and re-applying the load a few times, the resilient deformation becomes large compared with the permanent strain in one cycle, and a better estimate of stiffness may be obtained. Non-Linearity of response may be assessed by varying the stress levels in different cycles [11].
- **Dynamic Plate** - Both preceding tests are at non-representative rates of loading. This can be overcome by impact devices (of which the Falling Weight Deflectometer is the highest).
- **Dynamic Cone Penetrometer** - Permanent deformation could be assessed by the two previous tests if they were applied enough times. As this would be an unrealistic proposition, a cone is rammed into the ground by a repeatedly dropped weight. Thus a measure of shear strength is obtained. Often this ranks similarly to rankings of permanent deformation susceptibility.
- **Trial Compactions** - Trials involving full scale compaction and trafficking are the ultimate performance assessment method.
Permeability - In-situ permeability determinations can be made by injection of water into the base [12]. Certain assumptions of water flow régime have to be made. Inaccuracies in these assumptions will affect the results.

8. What are the gaps between theory & practice?

8.1. Permanent deformation (rutting) prediction
While our understanding of the resilient behavior of aggregate base materials is reasonably good. Both laboratory and in-situ determinations give rational values and variation in stiffness and deformation response throughout the pavement can be estimated by appropriate analytical techniques. The same cannot be said about permanent deformation which can only be ranked at laboratory scale. The data from such assessments have not yet been successfully used to produce an analytical (and hence predictive) tool for estimation of pavement rutting. This is due to the need to incorporate many effects (stress level and stress rotation for example) and to develop a satisfactory calculation procedure.

8.2. In-situ conditions of bases
Where satisfactory predictions of behavior are possible, then these rely on the test data having been derived at the correct moisture and stress conditions representative of the pavement base condition. While assumed conditions are widely available for design purposes, little is known about changes in moisture with season, rainfall event or life of the pavement. This hinders the optimum choice of material for the base and hinders the appropriate choice of ancillary works (e.g. drains, under-blankets, etc.).

8.3. Variability
Aggregate bases are known to vary in thickness, stiffness and permeability as a consequence of the raw material and of the construction process. The degree and consequences of this variability is poorly understood. This makes it difficult to determine the degree of importance of meeting the different aspects of a specification.

8.4. Polluting potential of ‘secondary’ aggregates in bases
While the use of performance-related test procedures should ensure that ‘secondary’ aggregates are compared fairly with conventional aggregates on the basis of their mechanical properties, they may introduce contaminants into the pavement structure by virtue of their own composition. While agencies concerned with environmental protection are understandably concerned about this possibility, the unknown is whether or not the contaminants can leave the material. For want of any better information, the general view at present is usually to reject material on which there is any doubt. This is almost certainly too restrictive, but the lack of knowledge of the hydraulic régime (Section 8.2), and the leach behavior of the wide variety of ‘secondary’ aggregates which may be proposed for bases, makes such a strategy almost inevitable.
8.5. In-situ recycling
More and more limitations on quarrying and restrictions on construction traffic are likely to force highway owners to consider re-using the existing pavement materials after in-situ treatment. Both old base and the material from higher and lower layers may be appropriate given the right processing after excavation. There is thus a need to define the appropriate strategy for in-situ re-use for the wide variety of materials which might be encountered. To cope with variation during reconstruction, rapid in situ assessment techniques need to be developed.

8.6. Optimising use of different materials
Associated with the need to optimise the re-use of existing pavement materials goes the need to optimise material use in general. With generic specifications and design guidelines, and the prevalent attitude that all aggregates for bases are the same, there is an urgent requirement for designers and owners to optimise design thickness for whole-life costing. At present it is difficult or impossible to estimate with any degree of precision the sensitivity of the pavement's performance to any change in base aggregate type, thickness, condition or treatment. This inability is mostly a consequence of the five areas of lack of knowledge mentioned briefly above.

9. Conclusions

This paper has sought to define the basic features of relevance to aggregates for pavement bases. It is concluded that aggregate bases will continue to be built and trafficked for the foreseeable future. The principle changes which may be expected are:
1] The increased use of mediocre quality and ‘secondary’ aggregates treated, where appropriate, by conventional or unconventional binders.
2] The use of performance-related test methods for mechanical and hydraulic properties for both assessment and compliance purposes as these will be the only fair method of comparing the wide range of candidate aggregates.

Finally, perhaps the time has now come for the delineated layering of a pavement into wearing course, levelling course, base and sub-base to be abandoned. To ensure optimum use of available but increasingly scarce resources requires engineers to use the available aggregates to the limit of their performance capabilities. If this involves application as a layer between the depths of the traditional base and the traditional sub-base then this should be encouraged and not hindered by outdated terminology.

10. References

1 Dawson AR (1994) Prediction of in-situ mechanical performance of unbound aggregate, is it possible?, Center for Aggregates Research, Paper to 2nd Annual Symposium, College Station, Texas.


