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Review

Sustainable Road Design: Promoting Recycling and Non-Conventional Materials

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Abstract: Many factors impact on the sustainability of road maintenance, including the organization of road authorities, contract forms used, financing structure and, unfortunately, political interference and corruption. However, this paper reviews the opportunities to increase sustainability by utilizing less environmentally damaging material sources, and also the associated challenges. It is a field that has seen advances in recent decades, for example in the effectiveness of cold-mix asphalt binders. Nevertheless, the opportunities are not being taken up in many countries, and this reflects uncertainty in predicting performance. This paper reviews the different design methods available, developed in both temperate and tropical climates, and highlights the lack of agreement with regard to non-conventional materials. The different sources of uncertainty and risk are then discussed, together with ways of limiting them. It is found that, while advances in performance prediction are highly desirable, the key to encouraging recycling and the use of inexpensive but non-conventional materials lies in development of the right contractual arrangements, specifically partnering and risk/reward sharing. The paper concludes with a discussion on approaches to partnering in the construction industry and the prerequisite climate of trust without which innovation is almost inevitably stifled.

Keywords: road; materials; recycling; non-conventional; risk; design; partnering

1. Introduction

The need to minimize use of scarce primary resources is becoming ever more urgent in most industries as humanity relentlessly exhausts this planet's ability to satisfy its demands and carelessly discards waste to the detriment of the environment. The roads industry is no exception to this. In the UK, for example, roads consume some 25% of all materials extracted from the ground [1] and, while most of these sources are not in immediate danger of becoming exhausted, the impact on the environment is substantial. Furthermore, even if exhaustion of resources has not yet occurred, the costs are real. For example, in relation to Malawi, Kamanga and Steyn [2] list material cost and/or shortage as a key reason for project delays. They suggest this is often because designs and specifications do not allow for the use of a possibly inferior but more readily available material, which would include recycled materials. And if, as reported by Oke et al. [3] in the case of Nigeria, failed asphalt is routinely discarded rather than being recycled, this in itself represents a direct and negative environmental impact.

Furthermore, the cost of road materials delivered to a construction site comprises two parts: The cost of the raw material at the quarry or gravel pit; and transport costs, both financial and environmental, which are frequently the higher of the two. Locally-available materials are obviously to be preferred. To this must be added the fact that if in situ recycling can be achieved, there are substantial time savings, beneficial for both the road authority and the user. Thus, the drivers are strong, both economic and environmental, in support of recycling and/or the use of locally-available materials.

The first objective of this paper is, therefore, to explore the reasons why many road authorities find it difficult to move from primary to secondary (e.g., industrial by-products), recycled or locally-available but possibly inferior sources. A further objective is to suggest the changes that have to be put in place if this move is to be made.

The paper identifies two areas where change is necessary. The first is technical and relates to the developments needed in design methodology in order to incorporate materials with non-standard properties. The second, and certainly more significant, is organizational and relates to the type of contractual arrangement that best enables such materials to be used. It will be suggested that management of the risk accompanying the use of non-conventional materials requires effective partnership between public and private sectors in a transparent and no-blame environment.

2. Barriers to Non-Conventional Technologies

It cannot be denied that road authorities are grappling with extremely difficult engineering issues. The passage of time and the seemingly ever-increasing numbers of commercial vehicles that use our road networks cause accumulated damage to road materials, damage which cannot be reversed. Road renewal/reconstruction will therefore continue to be required. One technology that is becoming increasingly conventional, and where the only barrier to uptake is investment in adapted plant, is so-called hot in-plant asphalt recycling [4]. Just as waste steel can be taken back to a foundry and incorporated into a new product, so waste asphalt can be taken back to an asphalt plant and incorporated into a new mixture. Researchers have established [5] that, so long as the percentage of recycled material is kept to a reasonable limit (30% in the case of the Federal Highway Administration in US) there should be no measurable loss of performance compared to a 100% virgin (i.e., primary aggregate) mix. However, the gain in terms of sustainability is modest. Resources are saved, and there is some reduction in energy demand but, depending on asphalt plant location, transport costs are still present.

Another conventional process is to hot-recycle an asphalt surface course in situ. Machines exist that have the capability to re-heat the surface to a depth of several centimeters to sufficient temperature for the asphalt to become pliant. This allows cracks to heal and the material to be re-compacted into a dense intact mat, usually with additional material added. This is proven technology and is used extensively. For example, Finlayson et al. [6] report on 25 years of successful experience in Canada. In terms of sustainability, this process is partially successful in that it cuts out transport costs. However, the energy cost is very high, and it has technical limitations in that it cannot treat problems deeper than a few centimeters.

The real ‘game-changer’ is cold in situ recycling. It has been done very successfully all over the world, e.g., in South Africa [7], India [8], Poland [9], with established design guidance available (e.g., [10]). Troeger and Widyatmoko [11] illustrated cost savings of 35–40% for different in-situ recycled solutions compared to conventional reconstruction, while a parallel estimate from Canada [12] was a 42% saving. One London borough [13] quoted a cost-saving ratio of over three between the two processes, and alongside financial savings reductions in environmental and disruption costs have also been documented [11].

But the problem with a game-changer is that new rules have to be formulated to govern the ‘game’. Companies such as Wirtgen [14] have been producing the necessary plant for decades, and there is a long-associated history of production of high-quality in situ recycled pavements. However, the resulting materials, though often subjectively ‘high-quality’, are distinctly different in terms of their engineering properties from conventional new materials [15], which means they do not fit easily into traditional pavement design methods.

The same difficulties arise with other non-conventional materials, notably those using industrial by-products such as fly ash or blast-furnace slag as partial binder replacements. Different materials with different properties require different designs. The following sections will review the range of non-conventional material types and the technical issues that currently present barriers to use.

2.1. In Situ and Ex Situ Recycling

Cold in situ recycling [16] is conceptually simple. A large rotary milling device breaks up the pavement to a specified depth and at the same time mixes in a binding or stabilizing agent, which may be cementitious or bituminous. At the back of the machine, a paving screed gives a reasonably smooth finish to the newly-created recycled layer, and this is followed by conventional roller-compaction. Depths up to about 250 mm can be treated in this way.

The term 'ex situ' is commonly used to describe an alternative, better controlled but more costly process in which the milled products are transported to a mobile mixing plant located on, or adjacent to, the site. Conventional mixing then takes place and the mixed material is transported, placed back onto the road, and compacted.

The key problem that recycling introduces is variability [17]. With both in situ and ex situ recycling, variability in the source material, i.e., the existing road, is unavoidable. In the case of in situ, there is likely to be additional variability due to differences in binder application rate and mixing efficiency. Increased variability relative to a virgin mix means that the performance of a cold recycled material will never exactly match that of conventional materials, thus requiring adjustment to design standards.

2.2. Cementitious Binders

Cementitious binders include conventional Portland cement, and if this is used to stabilize a material, then the resulting layer is in effect a weak concrete. This is a well understood class of material and is covered by standard specifications and design methods (e.g., [18]). However, in the context of renewal or rehabilitation of a road it comes with restrictions, and these limit its use.

If the new cement bound layer is designed to remain substantially intact under traffic, then it needs to be handled carefully. Typically, it must be left for seven days before it is strong enough to allow paving of another layer on top, and another layer is certainly needed in order to achieve the required surface level tolerances for anything other than the lowest of speeds. Furthermore, shrinkage due to hydration reactions combined with diurnal thermal cycles will eventually cause the new layer to crack into discrete lengths [19], and there is then the likelihood that these cracks will 'reflect' through overlying asphalt and require maintenance. Thus, this solution, though used, risks the need for significant future maintenance expenditure.

An alternative is to opt for a weaker material and accept that it will crack under construction traffic. No delay is then necessary before paving an overlying surface, and the danger of reflective cracking is diminished since cracks in the cement stabilized base, though numerous, will be individually less severe. On the other hand, the value of the recycled material is also diminished, relegating its properties to little more than those of an excellent granular base. This means that an increased thickness of new material has to be imported to site for overlying layer construction.

A more radical and much less conventional solution is to opt for a slow-setting binder, often a blend of hydrated lime with industrial by-products such as fly ash or ground granulated blast furnace slag [20,21]. Again, there is no need to delay construction, but the advantage here is that immediately after construction, the material is still in the relatively early stages of strength gain, and so long as early traffic loading is not too severe, there is every prospect that it will achieve a good final strength. The obvious problem is that this is difficult to tie down in terms of a conventional specification. If a material is not expected to reach its potential until several weeks after construction, how is it possible to control quality? In the UK, Highways England [22] have opted to test in situ and to assume a future strength gain, but any such approach inevitably carries risk. Yet the possibilities offered by this technique are highly attractive both technically and in terms of reduced environmental footprint. This difficulty represents another key point where design standards need to differ from those of conventional solutions.

2.3. Bituminous Binders

Since cold in situ recycling is carried out at ambient temperature, there is no opportunity to heat and form conventional hot-mix asphalt (HMA). The bitumen has to be delivered cold, and two widely-used products have been developed to do this: Bitumen emulsion and foamed bitumen. The binder arrives into the mixing zone in the form of tiny droplets (emulsion) or fine flakes (foamed bitumen) carried by water. The material is still effectively unbound during compaction. The compaction process itself then compresses the droplets or flakes of bitumen between aggregate particles, forcing them to adhere and thereby beginning the process by which a cold-mix asphalt is formed [23]. The process is a gradual one, and it is only as the water evaporates that the bitumen becomes ever more effective at binding the particles together, especially fragments of old asphalt surfacing that already contain bitumen.

The problem here is similar to that with slow-setting cementitious binders. If the construction is carried out well, the final state of the recycled layer will be that of an intact material with reasonably high strength, but this is not possible to verify during construction. Furthermore 'reasonably high strength' is still unlikely to be truly equivalent to a conventional HMA; for instance, a specific problem is that it is likely to have a reduced resistance to water attack [24]. Once again, conventional standards cannot be applied.

3. The Design/Specification Challenge

Both cold recycling and stabilization of locally-available, often secondary, materials are processes that can produce a cheap new pavement base with minimized environmental impact. The problem is that the materials with the potential to deliver the greatest economic and sustainability benefits also present the greatest challenge to engineers.

In essence, there are four significant technical barriers to implementation:

1. Recycled materials are inherently more variable than virgin mixes.
2. Material behavior, e.g., crack resistance, differs from conventional mixtures.
3. Water-susceptibility is often higher for recycled or stabilized mixtures.
4. Full strength can take many weeks or months to develop.

Undeniably each of these issues contribute to there being an appreciably higher risk attached to many non-conventional materials than is usually considered acceptable, and this risk has to be taken into account in design. For example, the widely used AASHTO (1993) method [25] requires the use of a coefficient to quantify the effectiveness of each material, and it has been suggested [26–28] that cold recycled materials should be assigned coefficients somewhere between 0.2 and 0.36. This compares to around 0.44 for conventional HMA, and means they would have to be 1.2–2.2 times as thick. Similarly, one of the highway authorities in the UK [29] recommends a thickness 1.33 times that of HMA. Others have taken a still more cautious approach and consider cold recycled materials as high quality granular layers, with equivalence factors of 1.4 or 1.5 (e.g., [30]—relating to Californian practice) times a conventional granular base.

In a given country or region, with materials and climate specific to that region, such an experience-based approach may be satisfactory. But it is not automatically transferable elsewhere. A more flexible, but potentially riskier, approach to design is given by so-called analytical methods, in which materials are typically defined by a stiffness modulus and a fatigue cracking law.

Valentin et al. [31] have made a thorough review of the way these methods have been applied to in situ recycled materials, revealing a large variety of approaches. In the UK, the design advice most commonly followed was developed by the Transport Research Laboratory [10], and three grades of material are specified in terms of their differing characteristic stiffness moduli. However, thickness is then determined from a chart, which is itself largely based on experience. In France [32], different stiffness modulus values are suggested depending on the proportion of Recycled Asphalt Pavement (RAP) included in the cold recycled asphalt layer. However, the calculations that follow do not include fatigue cracking of the recycled layer; i.e., it is treated as an already-cracked material. Similarly, in New

Zealand [33], in situ recycled materials are treated as superior unbound bases rather than having any intrinsic fatigue strength. In contrast, in Australia they are generally treated as slightly inferior asphalt layers, and a fatigue life is computed [33].

Thus, it is fair to say that many road authorities have found ways around the four barriers listed above. However, there is a lack of consistency, partially explicable by different typical road structures being used in different parts of the world. It is also fair to say that over the years there have been advances in prediction of the performance of roads incorporating non-conventional materials such as cold-mix asphalt [34–37] or in situ recycled layers [38].

Nevertheless, the four barriers listed above still significantly inhibit the take-up of recycled and other non-conventional materials. The following subsections consider each barrier in more detail.

3.1. Material Variability

Material variability is undeniably a negative feature of any in situ recycled material. Traditionally material variability has been dealt with in the same way as any other source of uncertainty, i.e., it contributes to the overall reliability of a design, and a client has to select a certain level of reliability appropriate to each class of road. In some methods, e.g., AASHTO (1993) [25], the client has freedom to choose; in others, e.g., Highways England [18], a certain probability of achieving the design life is built in, 85% in that case. But these methods were all developed based on experience of variability in conventional materials.

However, variability in recycled materials is different. The nature of the mixing process combined with variations in material type/quality along the road mean that there can be very large differences between small elements of material. These differences then tend to even out over larger areas, e.g., the >1 m diameter area stressed by a heavy goods vehicle tire. In a South African context, Lynch and Jenkins [39] report an increased variability between closely spaced test points in in situ recycled material. This is supported by the authors' own experience of a comparative trial on a newly-reconstructed pavement, in situ recycled against plant-mixed. Table 1 shows the results obtained.

Table 1. Comparison of tests on in situ recycled and plant-mixed base pavements.

Description	Test Method	Plant-Mixed		In-Situ Recycled	
		Mean	Coefficient of Variation	Mean	Coefficient of Variation
Modulus from tests on cores	Indirect tensile; BS-EN 12697-26 [40]	4960 MPa	17%	3930 MPa	58%
Modulus over a larger area	Falling weight deflectometer	3890 MPa	24%	2460 MPa	28%

The implication is that defects that are the result of combined effects from a relatively wide area, e.g., rutting, will show similar variation to that expected with plant-mixed materials; on the other hand, localized defects, e.g., cracks, will be much more varied in terms of when they first appear. Thus, in the common case of an in situ recycled layer overlaid by a relatively thin asphalt surface, localized surface cracking may appear over localized weak spots in the recycled base. For in situ recycled material, this negative feature has to be understood and either a reduced reliability has to be accepted or else the design needs to be modified to give the same reliability as for plant-mixed materials. In either case, there will be increased uncertainty and this has to be managed, both technically and contractually.

3.2. Unconventional Material Behavior

Unconventional material behavior is another difficult problem and is the subject of ongoing research, e.g., [41]. In essence, the materials under discussion can be classed into one of three material types:

- Strong, cementitious binder;
- Strong, bituminous binder;

- Weak, either binder.

The first of these is effectively equivalent to a normal cement-bound base and so can be considered as conventional.

The second however, if cold-mix binder (emulsion or foamed bitumen) is used, is not equivalent to conventional asphalt. Cold-mix asphalts are a class of material that can be described as partially bound [28], which means they start life with ready-formed and well distributed micro-cracks. In one sense, this is a disadvantage since the initiation phase of fatigue cracking is effectively bypassed. But in another sense, it is an advantage because the cracking that eventually occurs tends to be well distributed. This avoids occurrence of discrete large cracks [37], and reduces the stresses and strains felt by an overlying surfacing. Unfortunately, this is a level of complexity which the art of pavement performance modelling is not yet capable of addressing confidently, and this introduces additional uncertainty in performance prediction.

The third type will display unbound material behavior, but with a higher strength and stiffness than conventional unbound layers. In many design approaches, e.g., AASHTO (1993) [25] or analytical methods, this presents no problem so long as a realistic long-term modulus can be assigned, although this is something that currently relies more on experience than pavement science. However, in more restrictive design methods that rely on non-numeric descriptors for materials, recycled materials often do not fit easily into any conventional category. In such a case, it has to be accepted that the method cannot be directly applied.

The problem of unconventional behavior is one which is still being researched, bringing inherent risk, additional to that already identified due to material variability. Whilst the fruits of research may reduce these risks in the future, there is nevertheless a clear need for effective risk management.

3.3. Water Susceptibility

The problem of water susceptibility applies chiefly to cold asphalt mixes, whether recycled or not [24]. Many asphalts have a degree of susceptibility to water since aggregates are often hydrophilic. This means that if water can reach the bond between aggregate and bitumen it will gradually destroy it [42], although adhesion promoters incorporated into the asphalt can be effective at combating this problem.

Water ingress is a serious design challenge for all pavement types. Trapped water when pressurized by traffic loads softens soil, reduces the stiffness and shear strength of unbound materials, and also leads to breakage of cement and bitumen-bound materials [43]. In a conventional hot-mix asphalt, each particle of aggregate is fully coated by bitumen and it is difficult for water to gain access; in a cold-mix, the particles are not fully coated and water has a ready route in. It is therefore particularly desirable to keep water out of cold-mix asphalts, and the potential benefits will not be fully realized if water is allowed to gain access in large quantities. Preventative measures could include:

- Increasing the camber on the road;
- Installing/repairing functioning sub-surface drainage prior to recycling/re-construction;
- Re-sealing the road surface as necessary.

These are all practical steps that should lead to the water content within the pavement being controlled. However, the key point is that yet another source of risk is introduced, one that is difficult to design out completely and which therefore has to be managed contractually. And in a world in which the climate is changing rapidly in many locations, the magnitude of this risk is only likely to increase.

3.4. Delayed Strength Gain

In several of the materials under discussion strength may continue to develop for upwards of a year [44–46]. The long-term gain in properties therefore needs to be estimated as part of pavement design [47]. This is probably the hardest problem of all to deal with and it brings the issue of risk into sharp focus. This sub-section will therefore begin to introduce non-engineering aspects of risk management. The options appear to be:

- Specify tests on accelerated-cured laboratory specimens in order to predict in-road properties. However, material curing in the road depends heavily on ambient temperature, moisture availability, exposure to air, and level of compaction achieved. This means that the laboratory value can only give an indication of what would be possible under ideal conditions [48].
- Ask for contractor guarantees. However, there are many factors outside the contractor's control, which means that the guarantee will be expensive to the client. Furthermore, there may often be arguments the contractor can make to cast doubt on his responsibility for any perceived lack of performance.
- Partnering and shared risk/reward. This approach [49] acknowledges the inherent unknowns involved and is designed to avoid the confrontations and disagreements that are almost inevitable with either of the first two options. It removes the risk of punitive claims or penalties and allows engineers to make relatively unimpeded judgments.
- All risk is taken by the client. If both design and construction are carried out in-house by the client, then in theory this gives even more flexibility since there are no externally imposed requirements to satisfy.

It would seem unavoidable that simple reliance on a specification based on tests on laboratory-cured specimens—even accepting that the engineering community knows which tests to apply—is a recipe for uncertainty, early failure, and contractual dispute. And while contractor guarantees are logical and workable if restricted to defects that become apparent within a year or so of completion, this does not easily apply to road base materials. Thus, in the opinion of the authors, this technical difficulty, on top of the others introduced previously, simply cannot be overcome without first setting in place a means of taking and managing risk.

Figure 1 summarizes the above discussion relating to the four barriers identified. The next section will discuss further the critical issue of risk management.

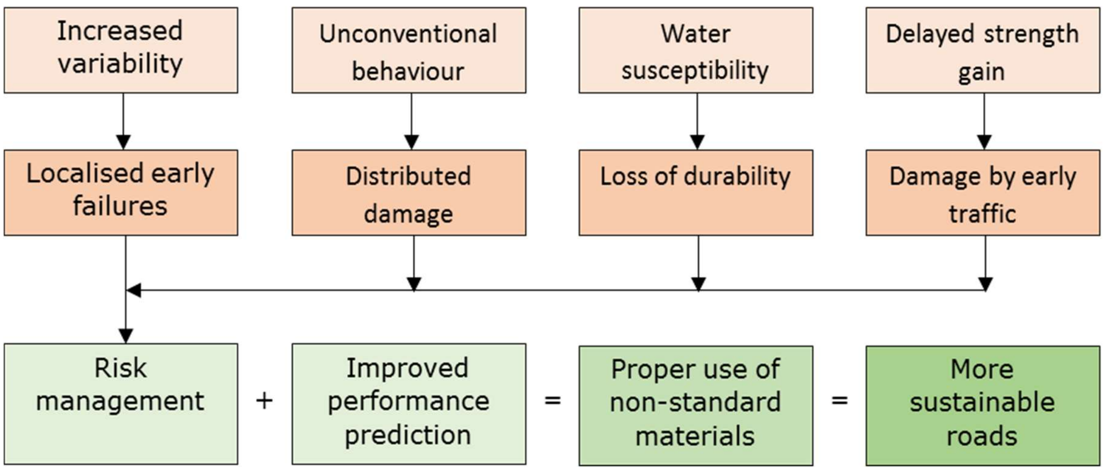

Figure 1. Summary of problems and solutions related to use of non-conventional materials.

4. Managing the Risk

Foregoing sections have made the point that improved engineering alone cannot overcome the risks associated with in situ recycling or the use of various types of non-conventional material. Thus, it is necessary to explore the means of providing an appropriate contractual climate to allow the risk-benefit balance to be managed properly.

Turning to the broad types of contractual arrangement possible, there is some evidence [50] that internal corruption is often less in the private sector than in the public sector, which suggests that keeping all activities within the public sector will not usually deliver an optimum result. It has also been noted that the use of sub-contractors often increases efficiency [51], which further suggests the benefits of private sector involvement. Furthermore, internal constraints from a risk-averse hierarchical client organizational structure may be hard to overcome and, it has to be conceded, many also lack technical expertise. Experience also suggests [52] that a performance-related incentive of some sort to an external organization (the contractor) leads to considerable benefit, and many would argue, e.g., [53] that partnering and the sharing of risk and reward is the optimum way to achieve this. Many studies have also come to the conclusion that public–private partnering in one form or another is the best way to stimulate innovation as well as handling project risk [54–56].

Public–private partnerships (PPPs) are widespread, but they vary enormously. In many cases, the motivation is finance, tying in banks as well as construction companies themselves, and these can be a means of procuring infrastructure developments that would have otherwise been unaffordable. For example, in an African context, Ajacaiye and Ncube [57] evaluate the potential of PPPs to contribute to development, and they are strongly supportive, based largely on the lack of available public finance in many African countries.

However, that has nothing to do with encouraging innovation; a bank may be even more risk-averse than a road administration. Leiringer [58] discusses the concept of 'design freedom' commonly promoted as a benefit of PPPs, and finds that in practice this freedom is easily stifled. There are pressures to control uncertainty at the bid stage; restrictions are often written into the contract, for example, to follow an established standard; and the more that risk is placed on the contractor's shoulders, the greater is the incentive to fall back on standard solutions. Compared to other aspects of PPP, design innovation is easily forgotten [59] despite it featuring prominently in perceived risk factors [60].

Thus, if innovation such as the use of non-conventional materials is to be encouraged, then the PPP has to be deliberately set up to achieve this. Issues such as speedy delivery and meeting environmental or safety targets can of course still feature, but it is also necessary to build in measures that reward design whose benefits can only be seen in the long term. To achieve this, the nature of the partnership has to be deep and long-lasting.

'Alliancing' is a form of PPP [61] that has risen to prominence over the last decade, leading for example to the UK Institution of Civil Engineers' NEC4 Alliance Contract, brought out in 2018. Highways England have declared their intention to use alliancing on all future 'smart motorway' projects. Alliancing brings in the concept of zero blame, zero claims, and a pre-agreed cash flow, as well as risk/reward sharing. The concept is that a partnership (the alliance) is set up very early, with an integrated team from all the main parties involved [62]. This requires considerable up-front work by the client organization and self-evidently can only function effectively in a very transparent culture in terms of bidding and contract award.

Love et al. [63], reporting on Australian experience, suggest that the normal way that alliancing contracts work is that contractors are rewarded in three ways: (a) All direct project costs are fully reimbursed, whatever the outcome of the project; (b) an agreed percentage overhead is also paid; (c) performance incentive payments are paid (or penalties levied) according to success against a number of Key Result Areas (KRAs). These can often be primarily concerned with speed of delivery [62], but this is also the area where long-term performance-related measures can be written in, potentially with reward or penalty being deferred for several years. In the context of recycling or using local materials, KRAs related to environmental damage/preservation would also appear to be appropriate.

However, Love et al. [63] also evaluated by means of interviews the actual factors that drove innovation by individual members of staff. Their conclusion was that the details of the alliancing contract itself were important only in allowing a collaborative and transparent culture to develop. The real drivers for innovation by individuals were accountability, credibility, pride, and reputation. The implication appears to be that engineers will come up with innovative solutions, but only if they are given the right no-blame environment to work in. This is the real challenge that procurement agencies face.

They also face the continuing battle against corruption if such an environment is to be created, a subject for which there is a large body of literature related to the roads sector, e.g., [64]. Links to political patronage have been documented [65] as has endemism within the procurement sector [66]. As an example, Ntayi et al. [67] note that an estimated $107 M is lost to procurement-related corruption each year in Uganda, and they provide a detailed and thoughtful study reflecting on the causes, for example poor public sector pay. Snaith and Khan [68] even found that effective unit rates for road works varied as a function of the source of funding and they developed a model to quantify the effects of this corruption on national wealth.

However, a wide body of literature suggests that transparency makes corruption more difficult and therefore almost inevitably increases cost-effectiveness. For example, e-procurement systems can be used to avoid the danger of deals being done in secret. Its introduction in India and Indonesia has been analyzed [69], leading to the conclusion that either quality goes up (India) or delays are reduced (Indonesia). Neupane et al. [70] also report positive experience in Nepal, particularly an increase in the level of trust in the procurement process. They concluded that e-procurement cuts down on the opportunities for secret meetings between bidders and public sector officials.

Thus, the types of partnering suggested as being the logical means of encouraging use of non-conventional materials depend greatly on there being an appropriate level of transparency. The very real benefits of PPPs, particularly the alliancing model, have to be offset against the dangers of collusion and cartels [71] in the letting of PPP contracts, implying that achieving the desired outcome demands a transparent environment and suitable public scrutiny, supported by meaningful penalties.

5. Conclusions

This paper has set out the key issues that currently hold back the use of recycled and other non-conventional materials in road construction, concentrating particularly on the economically and environmentally attractive in situ recycling options. Several of these options have been shown to have real long-term benefits and to be highly cost-effective. It is therefore essential that the industry finds ways of making these benefits a reality, even if this means taking a rather different approach to procurement and design than has historically been the case. Research should target the following areas if in situ recycling and the use of secondary and other non-conventional materials is to develop as it should:

- Research that delivers guidelines covering the financial, institutional, procurement, and contractual arrangements necessary to facilitate sustainable forms of public-private partnerships.
- Research that delivers design and specifications for using recycled and non-conventional materials for building and maintaining water-resilient road pavements.

Of these, the first is considered to be the real key. Once risk and reward sharing are established within working partnership arrangements, then engineers and researchers will find ways to improve their predictive capabilities and therefore their designs, leading to greatly improved sustainability in road construction and maintenance.

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References

1. BGS. *Construction Aggregates. Mineral Planning Factsheet*; British Geological Survey: Nottingham, UK, 2011.
2. Kamanga, M.J.; Steyn, W.J.V.D.M. Causes of delay in road construction projects in Malawi. *J. S. Afr. Inst. Civ. Eng.* **2013**, *553*, 79–85.
3. Oke, O.L.; Aribisala, J.O.; Ogundipe, O.M.; Akinkurolere, O.O. Recycling of asphalt pavement for accelerated and sustainable road development in Nigeria. *Int. J. Sci. Technol. Res.* **2013**, *2*, 92–98.
4. Sivilevičius, H.; Bražiūnas, J.; Prentkovskis, O. Technologies and principles of hot recycling and investigation of preheated reclaimed asphalt pavement batching process in an asphalt mixing plant. *Appl. Sci.* **2017**, *7*, 1104. [CrossRef]
5. Stephanos, P.; Pagán-Ortiz, J.E. *Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice*; Report FHWA-HRT-11-021; Federal Highway Administration: Washington, DC, USA, 2011.
6. Finlayson, D.; Nicoletti, C.; Pilkington, I.; Sharma, V.; Teufele, B. British Columbia's success with hot-in-place recycling—A 25 year history. *Proc. Can. Tech. Asph. Assoc.* **2011**, *56*, 185–201.
7. Jenkins, K.J.; Collings, D.C. Mix design of bitumen-stabilised materials–South Africa and abroad. *Road Mater. Pavement Des.* **2017**, *182*, 331–349. [CrossRef]
8. Bhavsar, H.; Dubey, R.; Kelkar, V. Rehabilitation by in-situ cold recycling technique using reclaimed asphalt pavement material and foam bitumen at vadodara halol road project (SH87)—A case study. *Transp. Res. Procedia* **2016**, *17*, 359–368. [CrossRef]
9. Dolżicki, B. Polish experience with cold in-place recycling. *Mater. Sci. Eng.* **2017**, *236*, 012089.
10. Merrill, D.; Nunn, M.; Carswell, I. *A Guide to the Use and Specification of Cold Recycled Materials for the Maintenance of Road Pavements*; TRL611; Transport Research Laboratory: Crowthorne, Berks, UK, 2004.
11. Troeger, J.; Widyatmoko, I. Development in road recycling. In Proceedings of the 11th International Conference on Pavement Engineering and Infrastructure, Liverpool, UK, 15–16 February 2012.
12. Alkins, A.E.; Lane, B.; Kazmierowski, T. Sustainable pavements: Environmental, economic and social benefits of in situ pavement recycling. *Transp. Res. Rec.* **2008**, *2084*, 100–103. [CrossRef]
13. Construction News. Enfield Saves Big with Insitu Road Recycling. *Construction News*, June 2012.
14. Wirtgen. *Wirtgen Cold Recycling Technology*; Wirtgen GmbH: Windhagen, Germany, 2011.
15. Karlsson, R.; Isacsson, U. Material-related aspects of asphalt recycling—State-of-the-art. *J. Mater. Civ. Eng.* **2006**, *18*, 81–92. [CrossRef]
16. Milton, L.J.; Earland, M. *Design Guide and Specification for Structural Maintenance of Highway Pavements by Cold in-Situ Recycling*; Transport Research Laboratory Report TRL386: Crowthorne, Berks, UK, 1999.
17. Zaumanis, M.; Oga, J.; Haritonovs, V. How to reduce reclaimed asphalt variability: A full-scale study. *Constr. Build. Mater.* **2018**, *188*, 546–554. [CrossRef]
18. Highways England. *Pavement Design. HD26/06 Design Manual for Roads and Bridges 7(2) Part 3*; Highways England: London, UK, 2006.
19. Pittman, D.W.; McCullough, B.F. Development of a roller-compacted concrete pavement crack and joint spacing model. *Transp. Res. Rec.* **1997**, *1568*, 52–64. [CrossRef]
20. Juenger, M.C.G.; Winnefeld, F.; Provis, J.L.; Ideker, J.H. Advances in alternative cementitious binders. *Cem. Concr. Res.* **2011**, *41*, 1232–1243. [CrossRef]
21. Hicks, J.K.; Caldarone, M.A.; Bescher, E. Opportunities from alternative cementitious materials. *Concr. Int.* **2015**, *37*, 47–51.
22. Highways England. *Design Guidance for Road Pavement Foundations (Draft HD25)*; Interim Advice Note 73/06 revision 1; Highways England: London, UK, 2009.
23. Miljkovic, M.; Radenberg, M. Effect of compaction energy on physical and mechanical performance of bitumen emulsion mortar. *Mater. Struct.* **2016**, *49*, 193–205. [CrossRef]
24. Valentin, J.; Montschein, P.; Fiedler, J.; Mollenhauer, K.; Batista, F.; Freira, A.C. *Report on Durability of Cold-Recycled Mixes: Moisture Susceptibility*; Conference of European Directors of Roads (CEDR): Brussels, Belgium, 2015.
25. AASHTO. *Design of Pavement Structures*; American Association of State Highway and Transportation Officials: Washington, DC, USA, 1993.
26. Davis, K.; Timm, D. *Recalibration of the Asphalt Layer Coefficient*; Report 09-03; National Centre for Asphalt Technology: Auburn, AL, USA, 2013.

27. Labuz, J.; Tang, S.; Cao, Y. *Structural Evaluation of Asphalt Pavements with Full-Depth Reclaimed Base*; Report MN/RC 2012-36; University of Minnesota: Minneapolis, MN, USA, 2012.
28. Khosravifar, S.; Schwartz, C.H.; Goulias, D. Mechanistic structural properties of foamed asphalt stabilised base materials. *Int. J. Pavement Eng.* **2015**, *16*, 27–38.
29. Babtie. *Road Pavement Design Guide*; Kent County Council: Maidstone, Kent, UK, 2000.
30. Jones, D.; Fu, P.; Harvey, J.; Halles, F. *Full-Depth Pavement Reclamation with Foamed Asphalt: Final Report*; Research Report UCPRC-RR-2008-07; University of California: Berkeley, CA, USA, 2008.
31. Valentin, J.; Montschein, P.; Fiedler, J.; Mollenhauer, K.; Batista, F.; Freira, A.C. *Report on Incorporation of Cold-Recycled Pavement Layers in Empirical and Mechanistic Design Procedures*; Conference of European Directors of Roads (CEDR): Brussels, Belgium, 2014.
32. LCPC. *Retraitement en Place à froid des Anciennes Chausées*; Guide Technique; Laboratoire Centrale des Ponts et Chaussées: Paris, France, 2003.
33. Browne, A. Foamed bitumen stabilization in New Zealand—A performance review and comparison with Australian and South African design philosophy. In Proceedings of the 25th ARRB Conference, Perth, Australia, 28–30 August 2012.
34. Liebenberg, J.J.E.; Visser, A.T. Towards a mechanistic structural design procedure for emulsion-treated base layers. *J. S. Afr. Inst. Civ. Eng.* **2004**, *463*, 2–8.
35. Kuna, K.; Thom, N.; Airey, G. Structural design of pavements incorporating foamed bitumen mixtures. *Proc. Inst. Civ. Eng. Constr. Mater.* **2018**, *171*, 22–35. [CrossRef]
36. Perez, I.; Medina, L.; Del Val, M.A. Mechanical properties and behaviour of in situ materials which are stabilised with bitumen emulsion. *Road Mater. Pavement Des.* **2013**, *14*, 221–238. [CrossRef]
37. Lacalle-Jiménez, H.I.; Edwards, J.P.; Thom, N.H. Analysis of stiffness and fatigue resistance of cold recycled asphalt mixtures manufactured with foamed bitumen for their application to airfield pavement design. *Mater. De Construcción* **2017**, *67*, 127. [CrossRef]
38. Paige-Green, P.; Ware, C. Some material and construction aspects regarding in situ recycling of road pavements in South Africa. *Road Mater. Pavement Des.* **2006**, *73*, 273–287. [CrossRef]
39. Lynch, A.; Jenkins, K. Materials recycled using foamed bitumen stabilisation: What is their long-term load-spreading capacity? In Proceedings of the 15th AAPA International Flexible Pavements Conference, Brisbane, Australia, 22–25 September 2013.
40. British Standards Institution. *Bituminous Mixtures-Test Methods for Hot Mix Asphalt*; BS EN 12697: Part 26; British Standards Institution: London, UK, 2012.
41. Nasser, A.I.; Mohammed, M.K.; Thom, N.; Parry, T. Characterisation of high-performance cold bitumen emulsion mixtures for surface courses. *Int. J. Pavement Eng.* **2018**, *19*, 509–518. [CrossRef]
42. Canestrari, F.; Cardone, F.; Graziani, A.; Santagata, F.A.; Bahia, H.U. Adhesive and cohesive properties of asphalt-aggregate systems subjected to moisture damage. *Road Mater. Pavement Design* **2010**, *11*, 11–32. [CrossRef]
43. Wang, W.; Wang, L.; Xiong, H.; Luo, R. A review and perspective for research on moisture damage in asphalt pavement induced by dynamic pore water pressure. *Constr. Build. Mater.* **2019**, *204*, 631–642. [CrossRef]
44. Avirneni, D.; Peddinti, P.R.; Saride, S. Durability and long term performance of geopolymer stabilized reclaimed asphalt pavement base courses. *Constr. Build. Mater.* **2016**, *121*, 198–209. [CrossRef]
45. Beeghly, J.H. Recent experiences with lime-fly ash stabilization of pavement subgrade soils, base and recycled asphalt. In Proceedings of the International Ash Utilization Symposium, University of Kentucky, Lexington, KY, USA, 19 October 2003; pp. 20–22.
46. Kazmierowski, T.; Marks, P.; Lee, S. Ten-year performance review of in situ hot-mix recycling in Ontario. *Transp. Res. Rec.* **1999**, *1684*, 194–202. [CrossRef]
47. Tabakovic, A.; McNally, C.; Fallon, E. Specification development for cold in-situ recycling of asphalt. *Constr. Build. Mater.* **2016**, *102*, 318–328. [CrossRef]
48. Serfass, J.-P.; Poirier, J.-E.; Henrat, J.-P.; Carbonneau, X. Influence of curing on cold mix mechanical performance. *Mater. Struct.* **2004**, *37*, 365–368. [CrossRef]
49. Dewulf, G.; Kadefors, A. Collaboration in public construction—Contractual incentives, partnering schemes and trust. *Eng. Proj. Organ. J.* **2012**, *2*, 240–250. [CrossRef]
50. Kenny, C. Transport construction, corruption and developing countries. *Transp. Rev.* **2009**, *29*, 21–41. [CrossRef]

51. Wales, J.; Wild, L. *The Political Economy of Roads: An Overview and Analysis of Existing Literature*; Overseas Development Institute: London, UK, 2012.
52. ADB. *Guide to Performance-Based Road Maintenance Contracts*; Asian Development Bank: Manila, Philippines, 2018.
53. Osipova, E.; Eriksson, P.E. How procurement options influence risk management in construction projects. *Constr. Manag. Econ.* **2011**, *29*, 1149–1158. [CrossRef]
54. Lu, W.; Liu, A.M.M.; Wang, H.; Wu, Z. Procurement innovation for public construction projects: A study of agent-construction system and public-private partnership in China. *Eng. Constr. Archit. Manag.* **2013**, *20*, 543–562.
55. Nawaz, A.; Waqar, A.; Shah, S.A.R.; Sajid, M.; Khalid, M.I. An innovative framework for risk management in construction projects in developing countries: Evidence from Pakistan. *Risks* **2019**, *7*, 24. [CrossRef]
56. Tang, W.; Duffield, C.F.; Young, D.M. Partnering mechanism in construction: An empirical study on the Chinese construction industry. *J. Constr. Eng. Manag.* **2006**, *132*, 217–229. [CrossRef]
57. Ajakaiye, O.; Ncube, M. Infrastructure and economic development in Africa: An overview. *J. Afr. Econ.* **2010**, *19*, 3–12. [CrossRef]
58. Leiringer, R. Technological innovation in the context of PPPs: Incentives, opportunities and actions. *Constr. Manag. Econ.* **2006**, *24*, 301–308. [CrossRef]
59. Raisbeck, P. Considering design and PPP innovation: A review of design factors in PPP research. In Proceedings of the 25th Annual ARCOM Conference, Nottingham, UK, 7–9 September 2009; pp. 239–247.
60. Chan, D.W.M.; Chan, A.P.C.; Lam, P.T.I.; Yeung, J.F.Y.; Chan, J.H.L. Risk ranking and analysis in target cost contracts: Empirical evidence from the construction industry. *Int. J. Constr. Manag.* **2011**, *29*, 751–763. [CrossRef]
61. Clifton, C.; Duffield, C.F. Improved PFI/PPP service outcomes through the integration of alliance principles. *Int. J. Proj. Manag.* **2006**, *24*, 573–586. [CrossRef]
62. Ibrahim, C.K.I.C.; Costello, S.B.; Wilkinson, S.; Walker, D. Innovation in alliancing for improved delivery of road infrastructure projects. *Int. J. Manag. Proj. Bus.* **2017**, *10*, 700–720. [CrossRef]
63. Love, P.E.D.; Davis, P.R.; Chevis, R.; Edwards, D.J. Risk/reward compensation model for civil engineering infrastructure alliance projects. *J. Constr. Eng. Manag.* **2011**, *137*, 127–136. [CrossRef]
64. Zedillo, E.; Cattaneo, O.; Wheeler, H. *Africa at A Fork in the Road: Taking off or Disappointment Once Again*; Yale Center for the Study of Globalization: New Haven, CT, USA, 2013.
65. Lehne, J.; Shapiro, J.N.; Eynde, O.V. Building connections: Political corruption and road construction in India. *J. Dev. Econ.* **2018**, *131*, 62–78. [CrossRef]
66. Mahmoud, S.A.I. Public procurement and corruption in Bangladesh: Confronting the challenges and opportunities. *J. Public Adm. Policy Res.* **2010**, *26*, 103–111.
67. Ntayi, J.M.; Ngoboka, P.; Kakooza, C.S. Moral schemas and corruption in Ugandan public procurement. *J. Bus. Ethics* **2013**, *112*, 417–436. [CrossRef]
68. Snaith, M.S.; Khan, M.U. Deleterious effects of corruption in the roads sector. *Proc. Inst. Civ. Eng. Transp.* **2008**, *161*, 231–235. [CrossRef]
69. Lewis-Faupel, S.; Neggers, Y.; Olken, B.K.; Pande, R. Can electronic procurement improve infrastructure provision? Evidence from public works in India and Indonesia. *Am. Econ. J. Econ. Policy* **2016**, *83*, 258–283. [CrossRef]
70. Neupane, A.; Soar, J.; Vaidya, K. Evaluating the anti-corruption capabilities of public e-procurement in a developing country. *Electron. J. Inf. Syst. Dev. Ctries* **2012**, *552*, 1–17. [CrossRef]
71. World Bank. *Curbing Fraud, Corruption and Collusion in the Roads Sector*; World Bank: Washington, DC, USA, 2011.