Promoting the use of Green Construction Materials in Low Volume Roads in India

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Korea Green Growth Partnership

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Contents

Foreword

Promoting the Use of Green Construction Materials in Low Volume Roads in India

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Rural Connectivity is a critical component in the socio-economic development of rural people, as it provides access to amenities like education, health, marketing etc. The main thrust of rural roads in India under "Prime Ministers Rural Roads Scheme (PMGSY)" is to build a sustainable and environment-friendly road infrastructure.

As we face increased vulnerabilities to climate change coupled with a growing scarcity of raw materials and aggregates used in the construction of rural roads in India, we are also presented with opportunities to mitigate these effects and build resilience and sustainability in the 21st century. One way in which we can act in a timely and appropriate manner to meet these challenges is by encouraging the use of locally-available, low-cost, and alternative (thus "sustainable") materials that include both non-traditional natural soils and gravels, as well as alternative materials derived from industrial, mining and urban wastes, the latter being far more sustainable options. Use of local materials and technology could also actually create opportunities for local employment ("green jobs"), which is one of the objectives also of the Korea Green Growth Partnership (KGGP), with whose support this report has been prepared. This coupled with "environmentally optimized" rural road design is perhaps the only viable way forward. While India has seen several good initiatives, these remain somewhat confined to particular regions and/or pockets and have not moved effectively beyond being "pilot" initiatives.

This report shows that India can reap significant positive economic benefits by mainstreaming the use of such sustainable materials and technologies in rural roads construction. Many of these materials require additional research before they can be used on a wider scale in India and this should be done through full-scale trial sections that are used to back up laboratory studies. Techniques for monitoring and evaluating the results from such trials (as indeed, of the "mainstreamed" road sections themselves) would also prove critical to their sustained long-term use. Also of high importance would be setting up the right incentive framework for such initiatives, and also of training and capacity-building efforts alongside.

The Central Government and several State Governments have started taking these initiatives seriously. At the National Rural Roads Development Agency (NRRDA), we have already issued Guidelines for a mandatory use of innovative and green construction material and technology for 15% of the roads included in the overall PMGSY programme. Several other states are also following suit in their state-level rural access programmes. Active discussions are also in progress for increasing the share of these roads built through innovative technology/ material to 30% in the next phases of rural access programmes. We at the Ministry of Rural Development are committed to work with partners such as the World Bank and KGGP to realize the goal of mainstreaming of the use of locally available, low-cost material in rural road construction, which would in turn help India transition towards a low-emissions, climate-resilient development path in the future.

Acknowledgments

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The activity was led by Arnab Bandyopadhyay, and the team comprised Ashok Kumar, Rashi Grover, and Santosh Sahoo. The international consultants engaged for the study were Paige-Green Consulting. The team gratefully acknowledges the useful insights and guidance received from Karla Gonzalez Carvajal and Shomik Raj Mehndiratta, and comments and advice provided by reviewers Simon D. Ellis and Mesfin W. Jijo. Thanks also to Phuong Thi Minh Tran for providing the team with international case studies.

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The picture on the cover page is courtesy Ministry of Rural Development, Government of India, and the team gratefully acknowledges the same.

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AIV	Aggregate Impact Value
BOF	Basic Oxygen Furnace
C&DW	Construction & Demolition Waste
CBR	California Bearing Ratio
CKD	Cement Kiln Dust
CRRI	Central Road Research Institute
CSIRO	Commonwealth Scientific and Industrial Research Organization
DCP	Dynamic Cone Penetrometer
DN	DCP Number
EAF	Electric Arc Furnace
EOD	Environmentally Optimized Design
FCBTK	Fixed Chimney Bull's Trench Kiln
FWD	Falling Weight Deflectometer
GGBS	Ground Granulated Blast Furnace Slag
GHG	Greenhouse Gas Emissions
ICT	Information and Communications Technology
IRC	Indian Roads Congress
KGGP	Korea Green Growth Partnership

KPa	Kilopascal
LCCA	Life Cycle Cost Analysis
LVR	Low Volume Roads
LWD	Lightweight Deflectometer
MORD	Ministry of Rural Development
NRRDA	National Rural Roads Development Agency
PCC	Portland Cement Concrete
PFA	Pulverized fuel ash
PI	Plasticity Index
PMGSY	Pradhan Mantri Gram Sadak Yojana
PSV	Polished Stone Value
RA	Recycled Asphalt
SADC	Southern African Development Community
SMME/SME	Small, Medium (& Micro) Enterprises
SWOT	Strengths, Weaknesses, Opportunities, Threats
T&I	Transport & ICT
UCS	Unconfined Compressive Strength
UTS	Ultimate Tensile Strength

Executive Summary

Executive Summary

This report is part of a series of reports being prepared with World Bank-Korea Green Growth Partnership (KGGP)-Australian Department of Foreign Affairs and Trade (DFAT) cooperation, climate resilience and green jobs being the central focus themes…

This study explores the possible **increased use of more sustainable road construction materials and technologies in rural roads in India**. This is a critical requirement in view of the increasing scarcity of traditionally used road construction material, high costs of transporting construction materials over distances as high as 400 km, and rampant environmental degradation, as well as other impacts caused by the mining of sand and aggregates (with climate change impacts) – all of which are unsustainable practices. It addresses the increasingly felt need to make investments "climate-smart" by addressing both climate change mitigation and adaptation aspects of the rural roads constructed. In doing so, it also elaborates on the potential to actually create opportunities for local employment ("green growth"). Green growth and building climate resilience are also some of the objectives of the KGGP. It may be noted that this is the first of a series of reports/deliverables planned with KGGP-World Bank cooperation in this area. The other deliverables include a detailed **Guidelines on the use of environmentally optimized designs for low volume rural roads in India**, and the associated **training material** which is foreseen to have widespread implications towards dissemination and eventual mainstreaming of these practices. Issues such as Greenhouse Gas emissions are mentioned but not discussed in detail as this is a field of study on its own.

The report (along with the series of reports under preparation) complements the climate change action plan of the Transport & ICT Global Practice as well as the Bank's overall mandate to operationalize the climate change agenda…

By aiming to build resilience and robustness with a focus on rural roads, this report seeks to address both the **climate change mitigation and adaptation aspects** as they relate to the rural road landscape in India. This would help in contributing to both the Bank's global and corporate agenda with respect to climate change, and also to the Transport & ICT Global Practice's aim of mainstreaming climate change mitigation and adaptation aspects in the road sector.

In doing so, it builds upon the extensive and valuable work done by the Practice in other regions, particularly East Asia…

The report, in particular, derives lessons from Bank work in some of the countries in East Asia, where arguably population density and rainfall are closer to the situation in India. For instance, it draws from the experiences of colleagues in **Vietnam**, where the condition monitoring of trials has resulted in the assembly of a significant amount of data on the performance of a wide variety of pavement and surfacing types under the **Rural Road Surfacing Research Programme** which included the evaluation of a representative selection of 269 WB-funded road links from 16 provinces in the country. Implications for pavement and surfacing selection and design, sustainability of unsealed gravel surfaces, and most importantly, the use of whole life costs and environmentally optimized design, have been taken into account.

The report begins by identifying the general requirements of road construction materials and then summarizes the range of natural material types that are available for use in road construction, although these may largely not be sustainable…

A number of factors that would normally exclude the use of such materials according to traditional norms and specifications are then discussed. For low volume roads in particular, many of these norms are inappropriate and can be modified for the use of local natural materials, due to their specific properties. However, despite this, the use of **natural gravels in road construction** is not a sustainable option in the long-term, thus other material options should be pursued in the interest of sustainability.

It goes on to explore the use of recycled in-situ materials and by-product materials in road construction, many of which show promise but may be excluded from general use in roads according to the current standard specifications for road materials…

The practice of **cold *in situ* recycling** of existing road materials, usually with the addition of cement or bitumen to improve their properties, using purpose-made recycling equipment is becoming the norm in many countries. A number of the machines are available in India and it is expected that there will be a significant increase in the re-use of existing road materials. The use of **alternative by-product materials** (generally termed waste materials) is highly sustainable with numerous environmental and long-term benefits. Increased usage of such materials will result in less environmental pollution (for example, reduced leaching and dust) and the release of valuable land currently "frozen as waste dumps", particularly in urban areas. Many of these by-products have unique properties that could affect their usage, which need to be identified and catered for, but can be valuable construction materials, nevertheless. Although many of these materials can be treated as "normal gravels", the specific types of testing required for some of them are noted.

The report compares current Indian low volume road construction practice with international practice and finds that there is scope to implement some of the innovations to better advantage…

There is a wide variety of concepts being implemented internationally, but many of these consist of adapting conventional materials and pavement design to low volume roads, which restricts the creativity of the techniques significantly. Only **Australia, Brazil and southern Africa** have really moved forward with innovative materials and pavement design procedures for low volume roads. A number of these technologies are included in some of the Indian design manuals, but these are unfortunately not being implemented to maximum advantage as yet. These include issues such as simple and innovative material characterization procedures.

Many of the materials identified in this report may require additional research before their wide-scale use in India and this should be done through full-scale trial sections that are used to back up laboratory studies…

The Indian literature shows that much **research** has been carried out on a wide range of by-product materials, but in general, there does not seem to be acceptance of this work for implementation. Studies of a number of the papers indicate that most of the results are preliminary and few final documents indicating "hard and fast methods" for the use of the materials exist. The report then looks briefly at some of the sustainability benefits that would accrue from the increased use of by-product materials.

…but there are some "low-hanging fruit" which include methods for improvement of unsuitable materials through techniques such as mechanical and chemical stabilization which are proven and time-tested in India and can thus be scaled up relatively easily, but just need to be carried out in a more scientific manner…

Many of the materials that are currently being used in India through necessity (better materials are not available) are very poor and need to be improved. This can be done using mechanical or chemical stabilization. The simplest form of **mechanical stabilization** is increased compaction effort – the majority of PMGSY projects currently use old equipment that does not produce high levels of compaction. Heavier equipment will result in significantly higher densities and consequent strengths for little extra cost, resulting in large potential savings in material usage. Mechanical stabilization through the blending of two materials is a cost-effective way of improving the materials. Local clayey silt and other fine materials can be blended with sands, local by-product materials (e.g. crushed waste bricks, builder's waste, etc.) to produce materials suitable for support or even structural layers.

However, each situation has to be investigated experimentally in the laboratory to optimize the blend ratios. If mechanical blending is ineffective, **chemical treatment** with lime, cement, pozzulana, fly ash, or combinations of these can usually be used to improve the material properties. Such stabilization has been used in India, but needs to be carried out on a more scientific basis, in order to optimize the stabilizer type and content, and produce the most cost-effective products. There are many proprietary products available for chemical treatment of soils, but few of these will produce the same result as traditional chemical stabilization at a lower cost. Each of these products needs to be tested with local materials, individually, before use in order to assess their cost-effectiveness.

Some of the other "**low-hanging fruit"** identified by the report include, for instance, the **use of slag materials, "Recycling" of mine wastes, use of products such as fly ash, phosphogypsum, Granulated blast-furnace slag, etc., and use of recycled asphalt (RA)**, which are relatively tried and tested internationally, and can be scaled up quite easily in India with little additional research**.** Other less-established technologies using unusual by-product materials will need to follow the traditional research process.

The report then moves on to discussing gaps in Indian practice…

There are a number of good design guides, manuals and specifications being used in India, based on past local experiences. Many of these also include innovative procedures, but these too, are not being implemented to maximum advantage. It is important that these technologies be implemented and assessed for usefulness – should there be any shortcomings, the documents can be improved over time. A number of gaps in these documents have been identified and highlighted; a SWOT analysis has been carried out to determine areas that can be improved which would lead to future benefits.

It lays particular and careful emphasis on the aspect of monitoring and evaluation (both of trial sections and 'mainstreamed' ones)…

With any innovation, it is essential that full-scale trial sections are constructed and carefully monitored and evaluated. This has been done repeatedly over many years, but unfortunately, with changes in staff and funding, very few of these are taken to good conclusions. As a result, performance, maintenance requirements and life-cycle cost analyses are not always fully documented. Many of the trials do not have proper control sections against which the performance of the innovative technique can be compared. This is a major problem in determining the effectiveness of the innovation. Techniques for developing trial sections and monitoring and evaluation of the results are described in the report.

…and ends with a call for building an overall 'enabling environment' for the mainstreaming of local and marginal materials in rural roads, at its core being a new approach to training of engineers.

The report lays importance on developing a programme of **research** that will determine financial values for issues such as the use of non-renewable natural resources (e.g. a realistic, aggregate tax), environmental benefits (e.g. release of land, reduced pollution) and other sustainability issues. It also suggests that studies of **overall cost/ benefits** on each potential product be initiated in order to justify their introduction and convince otherwise skeptical practitioners of the potential benefits. This will require individual investigations of each material and the local cost and competitive product conditions.

On incentive structure and institutional issues, the report discusses a new approach to the **training of engineers,** which should be central to an overall strategy that would involve at its core the creation of national and state-level **"champions"** through the use of **specific and sustained training.** This would include technical training, as well as training to address resistance to change within their organizations, and instruction in the location, sampling, testing, use and monitoring of such materials and their performance**.** The supporting enablers to this core strategy would include implementation of "technology demonstration projects", PPP-based research using a form of the 'Korean model' This involves research and academic institutes playing a key role in mainstreaming the use of alternative materials and technologies by inviting interested private sector agencies to be partners in their research programmes. The institutes then use a combination of their own and private sector funding to conduct the core research, offering the right incentives, focusing on awareness and communication, developing an asset management strategy including spot-monitoring, and an effective monitoring framework.

Specific recommendations may well have applicability beyond rural roads – and could be applied to national and state highways in certain cases, with suitable modifications, if required. The report notes that use of by-product and local materials is not restricted to low volume roads and, in fact, materials such as slag, fly ash and construction waste can even be used for many roads not classified as low volume.

1. Introduction

1. Introduction

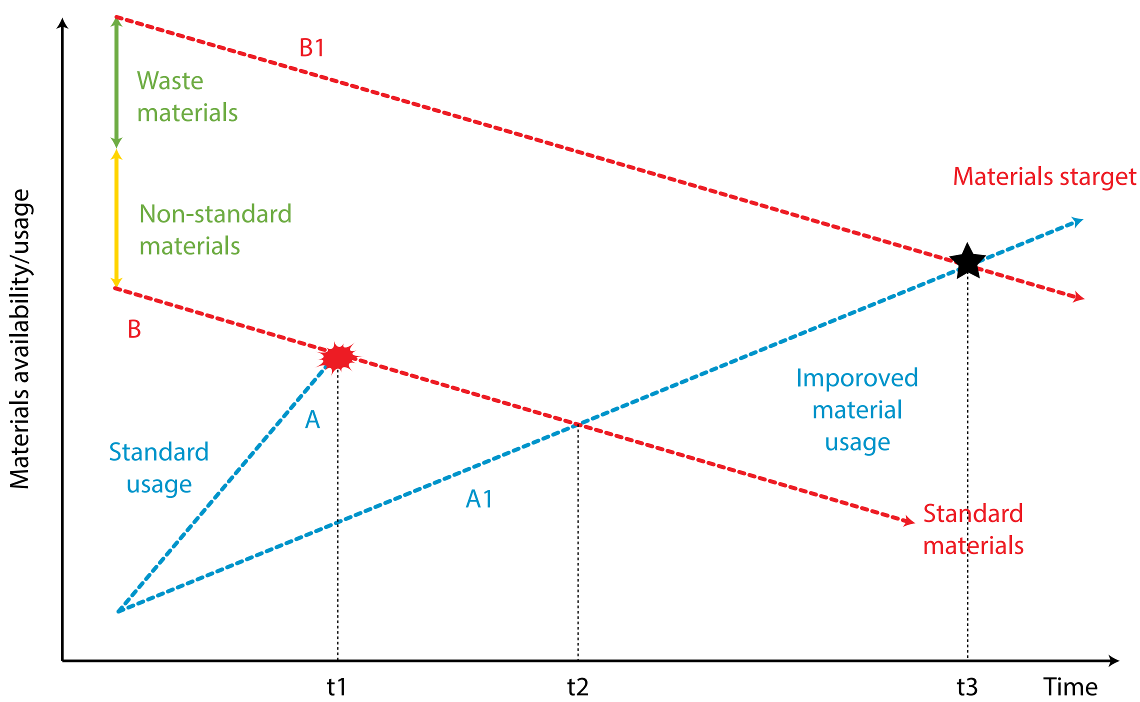
1.1 Background

The availability of construction materials in many countries is becoming increasingly constrained as suitable materials are rapidly being depleted. The increasing need for environmental preservation and "Green" issues are also changing the road construction milieu.

This is leading to increased costs for obtaining and hauling material, and also long haulage distances. This in turn causes damage to the existing road infrastructure as well as increased vehicle emissions and possible construction delays.

Figure 1 illustrates the potential benefits of innovatively using natural and alternative materials for road construction. It can be seen that continued use of existing material standards (standard usage – blue line A) and

Figure 1: Impact of increasing the use of non-traditional road construction materials

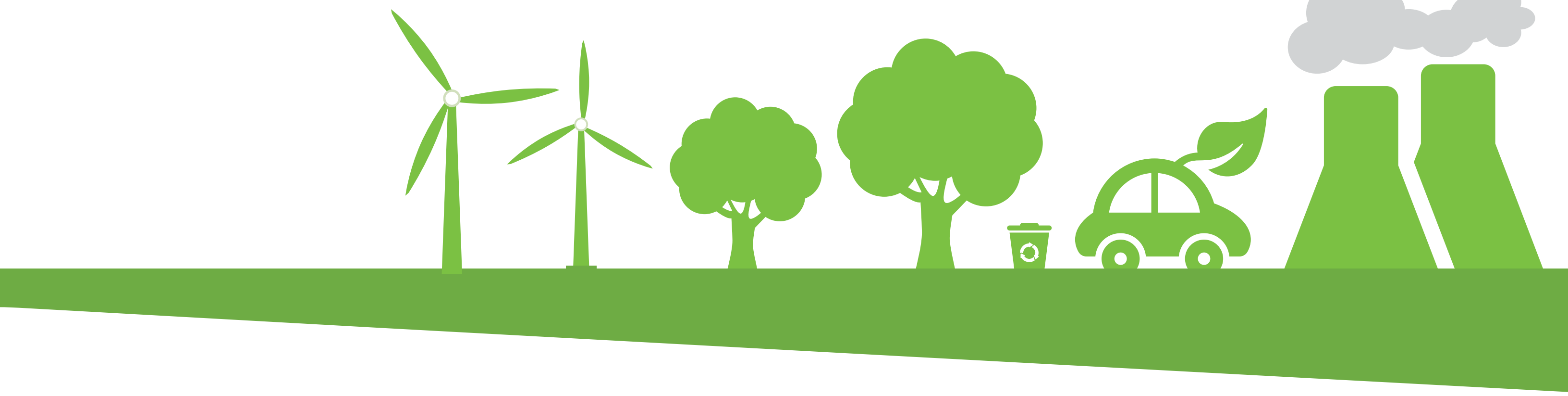


standard materials (red line B) will result in depletion of potential sources at time t1. The increased availability of natural materials can only be achieved by changing the required materials standards to those more appropriate for the road category, i.e. using material of lower material standards that is more suitable for lower volume roads. This will also reduce the cost of construction materials and will result in the potential to build more roads (shown as improved material usage in Figure 1 by the blue line A1). By doing this, the life of the existing natural material sources can be extended to time t2 (Figure 1). However, by increasing the use of alternative materials (by-products or what are now considered to be waste materials as well as materials not complying with current specifications), the availability of construction material resources will be significantly increased (red line B1) and the time before usage exceeds availability will be extended to time t3.

Other "green" issues are strongly interrelated with the use of natural and processed materials. These include the energy required for their processing and usage, emissions related to their preparation and use and the non-renewable (unsustainable) nature of using many natural construction materials.

1.2 Purpose and scope of chapter

The purpose of this chapter is to identify the types and needs of construction materials for low volume roads, and to compare the current practice in India with international practice. Gaps in the current local practice in relation to international practice will be identified and possible ways of closing these will be introduced. Issues such as monitoring and evaluation of full-scale trial sections are also introduced.



2. Requirements of Road Construction Materials

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In order to minimize the cost of road projects, particularly those carrying light traffic, materials used in their structural layers should be sourced as close to the project as possible (haulage costs are frequently the highest component of material provision) and should be of the most appropriate standard for the respective layer. This means that the material should:

- provide the necessary strength or stiffness for the proposed layer in the road, without having excessively good properties, and,
- be able to retain those properties over the design life, and preferably longer, under the impacts of traffic and climate.

Standard material test techniques and material specifications have been developed to assess the quality and durability of road construction materials over the past century or so. Unfortunately, many of these have not been reviewed for the past 70 or 80 years and are still applied in the standard manner, despite numerous changes to road design philosophies over this period. An example of this is the almost international use of a minimum soaked California Bearing Ratio (CBR) of 80% and a maximum plasticity index of 6% for all base course materials irrespective of traffic and environment. It is well known that both of these tests have different protocols in different countries, and thus produce different results, and yet the same limits are used. It should also be noted that a CBR of 80% for base course materials is used widely, irrespective of the need of the road, i.e., the specification is applied to roads carrying 1,000,000 standard axles as well as those designed to carry only 10,000 standard axles. This results in avoidable wastage of material that is best conserved for roads carrying much higher traffic loadings and upgrading of low volume roads for higher traffic in the future.

It is thus essential that appropriate specification requirements are introduced for different categories of low volume roads, taking into account the main properties required, as well as the appropriate test methods. This is particularly important for lightly trafficked rural access roads, where the traffic and loads imposed on most roads are minimal. Significant economies can thus be made by using material appropriate for the specific pavement characteristics. The design philosophy should be changed from "finding materials to suit the proposed pavement design" to "designing the pavement to suit the available materials".

The main requirements of materials in the structural layers of roads are to provide an adequate strength or stiffness to avoid shear failure or traffic-induced compaction in the sub-grade, and to retain these properties over the expected life of the road, i.e. to be durable. It should be noted that traffic-induced compaction (or rutting) can be almost totally eliminated by ensuring that the material is compacted to as high a density as possible (exclusion of as many voids as possible). Recent developments and research have indicated that the plasticity is in fact inherent in the strength of a material, together with other properties and in most cases, provided that the strength requirements are met, the plasticity is almost immaterial. It does, however, provide an indication of the potential moisture susceptibility of the material. One of the problems of prescribing various "interrelated" properties is that if a material fails to satisfy one of these properties, it will be rejected for use. In this way, materials that easily satisfy the "most important" strength criterion, but are marginally deficient on the plasticity or grading will be rejected for use.

This chapter deals primarily with the materials used for the surfacing and structural layers of lightly trafficked roads. It also looks at possible means of improving the support materials so as to reduce the quantity of material required in the overall pavement structure.

It should be noted that there are still significant deficiencies in existing specifications for conventional materials when applied to non-traditional materials. Therefore, although certain "by-product" materials can be treated and specified according to conventional norms, there are many of these materials that require "adaptations" to existing specifications.

3. Local Natural Materials

3. Local Natural Materials

Local natural materials consist of those materials that are naturally in their current form (state) and position as a result of geological and geomorphological processes. These make up the bulk of materials currently used in road construction. Such materials would normally be classified into one of the following groups:

- Fresh/unweathered rock
- Residual soils
- Transported material
- Pedogenic materials

3.1 Fresh (unweathered) rock

Fresh or unweathered rock is ultimately the source of all of the above material groups. Fresh rock consists of igneous, sedimentary or metamorphic material that has undergone no (or very little) decomposition or alteration, and usually requires blasting, crushing and screening before its use in roads. Any environmentally-induced changes to the natural properties of the rock will be restricted to thin layers adjacent to joints and fractures in the material, where water has flowed and may have locally affected small volumes of the entire rock mass, without causing deterioration of the larger material volume processed for construction.

These materials, depending on the rock type and origin, will generally provide high quality, durable aggregates after excavation, crushing and screening. However, they are costly materials, require the development of a quarry and are difficult to locate in or close to urban areas where environmental and mining issues often result in severe technical constraints and cost implications.

The use of fresh rock in low volume and rural access road structures should be limited to surfacing aggregates where appropriate, and concrete applications within the overall road system. There is seldom a need to use such high quality and expensive materials for pavement layers in low volume roads. Such materials should be conserved for use in higher standard roads in future.

3.2 Residual soils

Under natural environmental processes, fresh rock, when exposed to air, water and any other migrating fluids starts to deteriorate. Many of the minerals within the rock change their composition when actions such as hydrolysis, carbonation, leaching and other chemical and physical alteration processes occur. Most weathered or residual rocks therefore include particles with a wide range of properties. These would be from slightly weathered (minor staining of water flow paths) to completely weathered, in which all of the minerals with low resistance to alteration have been converted to new minerals (mostly clays) and the quality of the material for construction purposes has changed (both positively and negatively), entirely.

With this alteration, the physical properties of the rock deteriorate and the rock usually becomes more plastic with a significantly lower strength. However, such materials are much cheaper to construct with, as they can be processed using bulldozers and rippers, and seldom require blasting. Limited crushing of oversize materials may be necessary in some instances, and these options are discussed later in this chapter. A limited quantity of plastic fines is also usually beneficial to the construction process.

These materials can be tested using conventional test methods and probably provide the most economical materials for structural layers in low volume roads, when they occur in close proximity to the site. They are widespread, generally easy to locate and usually have short haulage distances. However, they can also cause many problems related to specific inherent properties such as high clay contents (in basic crystalline rocks) with swelling characteristics, high sodium contents leading to dispersive soil problems, high collapse potentials due to variable weathering, etc.

In many countries, however, these are the predominant materials used for the construction of structural layers in low volume roads and have been used with great success.

3.3 Transported material

Transported materials are those unweathered and weathered rocks that have been moved by gravity, water, wind or ice. They may be close to their original place of origin (e.g., gravity induced landslides or local colluvial deposits) or they could be many hundreds or even thousands of kilometers away from their origin (e.g. river alluvium).

Their mode and distance of transportation will affect their properties significantly. Landslide debris, for instance will contain exactly the same materials as those surrounding the area affected by the landslide. Alluvial deposits are similar to the source materials near the source. However, the softer and less resistant materials are reduced as they are transported, until the materials may be only quartzitic sand where they are released into the sea, or clay when deposited in large lakes having little water movement or deep marine environments. Along the river, the properties will vary significantly, but many good types of gravels for construction can be located adjacent to rivers. A similar situation exists with aeolian materials where the action of the wind sorts and separates the sands into different sizes and shapes as they move further away from their source. Rockfalls usually comprise unweathered materials and would need to be treated as a natural rock material, despite often occurring as a finer material.

These materials can be tested using conventional test methods but can have a wide range of properties. For instance, gravel layers in youthful stream areas can provide high quality materials with some simple crushing, while thick deposits of alluvial silts and clays (i.e. such as seen on the Ganga flood plains) typically have very low strengths. They can also be subject to similar stability problems (expansion, collapse, dispersiveness, etc.) as the residual materials described above.

3.4 Pedogenic materials

Pedogenic materials develop in residual or transported materials by the accumulation of certain binding elements that "cement" the *in situ* particles together. Typical minerals causing this cementation of other particles (which is actually a soil-forming process) include calcite (calcrete or kankar as found in Rajasthan), iron oxides and hydroxides (laterite and ferricrete), silica (silcrete), gypsum (gypcrete) and various other minerals or combinations thereof. The process can involve either the accumulation of the cementing material as a result of leaching out of soluble minerals leaving an insoluble residue of the cementing materials (e.g. laterite cemented by iron oxides and hydroxides), or the leaching in of the cementing material, which binds the soil particles that are in the area (often the case with kankar, cemented by calcite).

By their nature, these materials have highly variable and often unusual properties, which depend on the properties of the source material cemented by the "binders". This is a problem with some of the materials, as experience has shown that they can perform particularly well as road construction materials, despite their properties not complying with conventional specifications.

This is often both a function of their testing protocols, which can affect certain minerals in their composition. The standard processes of oven-drying the materials, for instance, as part of the preparation for testing, can change their plasticities and gradings significantly.

The laterites in India are of specific interest as they are the genuine so-called "Buchanan laterites" that harden on initial drying out. These would obviously be difficult materials to work with in road construction projects due to the limited time available for processing. In addition, they are considered as high quality building materials and probably too costly for road construction. However, experience in southern Africa and elsewhere has shown that these materials after drying out can be broken down and used successfully in road construction, where they continue to increase in strength (self-stabilization) with time. "Waste" laterites can thus certainly be considered as innovative road construction materials and should be investigated where they occur. One of the issues with such materials is that the "self-stabilization strength" only develops over time, apparently as a result of oxidation of the soluble ferrous iron to the less soluble ferric iron, and is not available during the early life of the road. However, this development of additional strength results in a progressively stronger road over time.

In many countries, (e.g. South Africa, Brazil, Australia, various SADC countries), specifications for the use of pedogenic materials have been developed. This allows the use of materials specific to a region, that do not comply with standard specification requirements, to be used in appropriate layers in roads and the widespread use of such materials. Such alteration of the existing specifications for these materials should be considered in India, but needs to be based on some fundamental research and investigation of pavements constructed with these materials.

3.5 Use of natural materials in roads

The strength behavior of natural gravel materials depends almost entirely on their gradation and mineral composition (the presence of clay minerals provides plasticity/cohesion). The strength of fine materials is primarily a function of their cohesion (related to the quantity and type of clay), which is highly moisture sensitive. The strength of sand and gravels on the other hand is related mostly to their frictional characteristics, which are more density related. Most soils consist of a mixture of clay, silt, sand and gravel particles, and their strengths are a combination of the cohesive and frictional characteristics contributed by the various fractions of each of these, making them both moisture and density sensitive.

The majority of road construction materials currently used internationally are natural gravels. Their continued use on a large scale is not, however, sustainable, environmentally friendly or economical. The use of crushed rock for upper pavement layers results in high costs, particularly for low volume roads, where natural gravels are generally perfectly adequate and effective and far more cost-effective. Replacement materials discussed below, would, however, be more sustainable and "**green**".

A good material for pavement layer construction consists of a blend of different components, being mostly gravel, with some sand, silt and clay. Materials with a paucity of gravel will be weak but can be improved by blending with a coarse component to provide more frictional resistance. Sufficient gravel should, however, be added to ensure that there is some inter-particle contact and the gravel is not surrounded by only clay and silt ('plums in a pudding"). Without inter-particle contact between the coarser sand and gravel components, the cohesive nature of the fines will dictate the properties of the material.

Crushed stone and natural gravels have been used almost continuously for more than 100 years. So their properties, deficiencies and problems are now relatively well understood and mostly adequately controlled by standard specifications which contribute to their continued use.

There is no doubt, however, that the time has come for change and the increased use of alternative "green" materials is essential. In many cases, it may be more prudent to phase out (or at least minimize) the use of crushed stone as far as possible, replacing it with natural gravels where practicable. In the meantime, a better understanding of the use and performance of by-product materials can be developed to replace the natural gravels, as more knowledge about the alternative materials becomes available.

4. Recycled *in situ* Materials

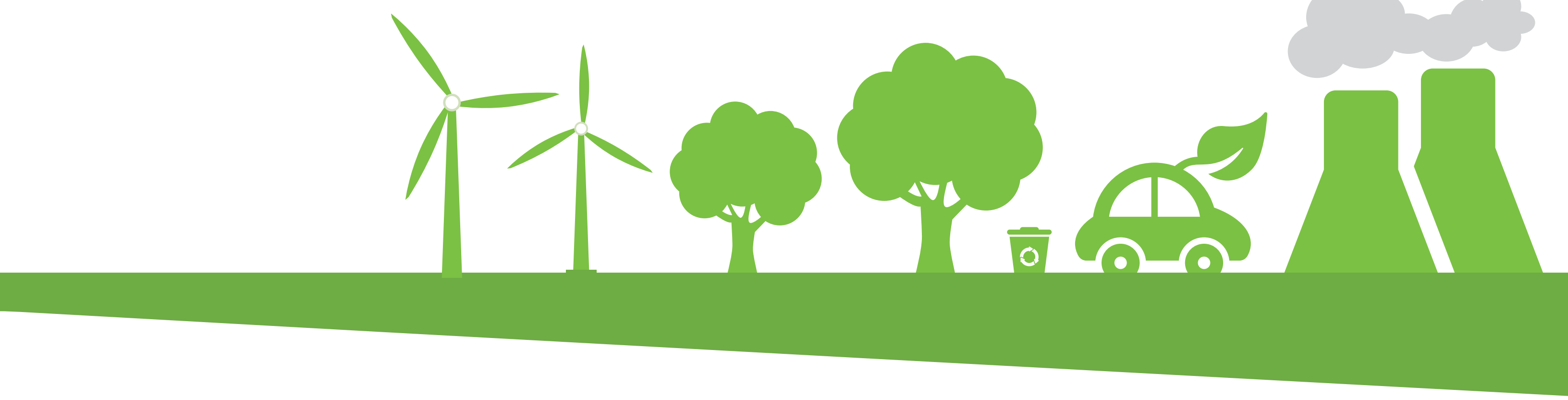
4. Recycled *in situ* Materials

Although the majority of low volume roads in India are being developed from old tracks and paths, the need to rehabilitate or reconstruct older and failed roads (preferably with minimal traffic disruption) is increasing rapidly. Relatively new technologies involving cold *in situ* recycling of such roads are highly cost-effective options. The technology to carry this out rapidly and effectively has developed in leaps and bounds over the past 10 or 15 years and the equipment, although expensive, is now relatively common among larger construction companies in most parts of the world, including India.

The main benefit of this technology is that the existing materials (mostly crushed stone and natural gravels) in the road are reused instead of importing new materials. However, this is usually with the addition of some new material and with the addition of a stabilizing or binding agent. Environmentally (and with major sustain ability benefits), this is an extremely valuable technology, minimizing the need to exploit new material sources. The ability to rehabilitate and construct roads in half-widths also reduces traffic accommodation costs and problems in constrained areas.

There are, however, problems and limitations with the technology that need careful design and supervision on any project. These include the variability of the existing materials in the road resulting from prior road repairs in the past, variable layer thicknesses, etc. and the usual procedure of widening lanes during recycling and the associated material properties (i.e. incorporating shoulders and new material over previously un-trafficked areas). These can be overcome with careful design, the correct choice of stabilizing agent and good supervision during construction. The understanding in this regard is increasing day by day around the world.

Large stockpiles of old road materials have been seen along many roads in India. In addition, a number of instances have been seen on low volume roads, where the asphalt carpet has been removed and discarded alongside the road. This material should be reused as far as possible, even if only as a crushed/broken material to provide a smooth surface for the new bituminous layer.



5. Use of By-product Materials

5. Use of By-product Materials

In order to promote "**greenness**" in road construction, the use of non-natural materials should be increased as far as possible. These include by-products from most industrial enterprises (e.g. mining, manufacturing, industrial, power generation, etc.) as well as wastes produced in the urban environment (small industrial, construction and demolition wastes and even domestic wastes).

These materials have mostly been through a severe comminution and often a heating process; they thus generally incorporate a significant quantity of "embodied energy" due to their primary processing (as opposed to using a lot of additional energy in their production for use in roads). Their use also involves considerably less emissions than the processing of an equivalent quantity of natural material.

There is a wide range of such materials available, many of which can be (and have been) used in structural layers for roads, while others can be used in lower support layers or as modifiers or stabilizers for improving materials. Common waste (or preferably termed "by-product") materials include, but are not limited to:

- Reclaimed bituminous material (RA)
- Crushed concrete
- Pulverized fuel ash (PFA or fly ash)
- Blast-furnace slag
- Steel slag
- Other metallurgical slags (e.g. chrome, manganese, copper, zinc)
- Aluminum industry wastes
- Colliery spoil
- Construction and demolition waste
- Mine and stone processing waste (marble, slate, granite, etc.)
- Phosphogypsum
- Used tires
- China clay sand

- Foundry sand
- Crushed waste brick
- Used rail ballast
- Furnace bottom ash
- Cement kiln dust
- Glass
- Spent oil shale

Some of the issues with the utilization of by-product materials are the variability often encountered in existing "waste" dumps due to uncontrolled disposal, as well as the unique properties of each type of by-product material. These need research into their individual characteristics and usage requirements. Another issue is that many of these products are, usually incorrectly, classified as hazardous or toxic wastes by environmental authorities and require special permits for their use. It is thus important that all potential waste materials be tested for toxins and environmental acceptability before substantial work is carried out on them. This is best achieved by working along the value chain of the material generation and disposal process. It would then be possible to sort the materials by their physical and chemical characteristics and stockpile them for ready use in various applications in road construction, and even for other building purposes. This requires a coordinated effort with the waste generators and all other stakeholders.

Research into the use of those materials that are found to be environmentally acceptable should be initiated. Those that are found to have potential "pollution" problems require some form of mitigation of the problems first, before significant effort and cost is applied to investigate their use in roads. Experience has, however, shown that when used in properly constructed pavement layers, the leaching of undesirable components into the surrounding material and groundwater is minimal. This is in fact usually far less detrimental than the harm caused by dust and debris washed off the pavement surface during rain and precipitation.

It is important that a complete inventory of all potential by-product and waste materials in India be made and kept up-to-date. This should be used as a "first-stop" when attempting to locate construction materials for projects. In addition, the increased reclamation and processing of products such as Construction and Demolition Waste (CD&W) should be urgently initiated.

A limited review of the Indian literature indicates that India is with the rest of the world in most respects regarding the possible use of by-product materials in road construction. Many by-products and other innovative construction materials and solutions have been reported on, with numerous excellent findings and conclusions. However, it appears that most of these seem to get left on the shelves and are not continued to a useful conclusion. This issue is discussed in more detail in Chapter 12.

Issues related to each of the waste products identified above are discussed below. It should be noted, however, that each of these materials has unique properties, which need to be investigated and researched in order to benefit optimally from their uses. This is, however, the type of research that can easily be carried out by researchers at universities and research institutions as part of post graduate qualifications (Master and Doctorate degrees). Many of these materials can be used in combination with local materials (e.g. fly ash and slag) and in these cases, specific investigations will need to be carried out with the various combinations because of the variability in the properties of the local natural materials.

Most material specifications do not refer to the use of by-product materials (other than slag) and details referring to the specific needs and use of such materials are presented in the discussion below.

5.1 Reclaimed bituminous asphalt (RA)

In most countries there are rapid developments in the re-use of milled, shaved and ripped up asphalt layers from pavements. Only a few years ago, engineers were wary of including more than about 10% reclaimed asphalt in new pavement layers. In the past year or two this has increased to at least 30%. In some countries, much higher quantities (up to 70% in Japan) are being used. In many countries now, 100% of all RA (including reclaimed asphalt, asphalt planings, etc.) is reused in pavement layers. One of the major benefits of using RA is that the material is commonly used in so-called "warm-mix" asphalt, with significantly reduced heating requirements and emissions.

RA is mostly used for bitumen-treated bases and wearing courses in high volume roads to obtain the best "value for money" (it has a high intrinsic value because of its high bitumen content). However, waste and contaminated RA could be used equally effectively as a substitute for gravel and aggregate in low volume roads if it is unsuitable for use in more expensive roads. The binder in RA requires certain properties before it is used in asphalt or bitumen-treated layers in Japan for instance (typically with a rejuvenator), and if these properties are not met it is not used. Use of these materials in the energy-efficient "warm mix asphalt" industry is increasing rapidly internationally. It is thus necessary to investigate these materials and develop appropriate specifications for their use, taking into account the unique properties attributable to their bitumen contents. It is also important to note that their use and the materials design process depend on the quantity and age of residual binders in the RA. Ongoing international research would give good pointers as to their property requirements and usage.

Examples have been seen in South Africa, where a fine (passing about 30 mm screen) milled RA used as a gravel wearing course material rapidly bonded together (under traffic and high ambient temperatures) to give what has become effectively a bituminous (asphalt) seal (foreground in Figure 2). The result was totally unexpected, and after about 2 years the layer was sealed with a slurry seal (background) to provide a very low-cost fully paved road.

Figure 2: RA originally used as gravel wearing in foreground before being covered with a slurry seal in the background to provide a paved road

The use of RA is a relatively new technology and considerable research is still required and being carried out. However, this research is nearly only for high trafficked roads, with little emphasis on using poor quality or reject RA for low volume roads. Work in this area should be initiated, as possible sources of this material have been regularly observed stockpiled along roads during travels around India. It is thought that a much lower quality of RA could be beneficially used for LVRs, where instances have been seen that the premix carpet has been removed from failed roads and spoiled. This material could easily and beneficially have been included in the new pavement layers.

5.2 Crushed concrete

Crushed concrete in this case is considered to be almost pure concrete derived from demolished concrete structures, discarded ready-mix leftovers or some other source consisting entirely of concrete. Materials described as Construction and Demolition Wastes (C&DW) often contain high proportions of concrete. However, they are mixed with other materials (mostly bricks and ceramic tiles with additional undesirable materials such as plastic conduit and wood) and are a much lower quality material. These are considered separately in this report.

Crushed concrete is a high quality material bearing in mind that it tends to be manufactured with strong and sound unweathered rock, or sand often derived from crushed rock or washed river sand. It typically contains in excess of 8% of Portland cement.

Crushed concrete, irrespective of age (concretes up to 60 years old have been checked), has a residual cement content that reacts with moisture when placed in the road and results in a "free" relatively highly stabilized layer. This could even be blended with local materials to increase their strength significantly. As the majority of this material is only available in large quantities in urban areas, its use is really only cost-effective close to such sources (probably within 50 km from an urban area source).

Its use, however, requires that the acquisition of such materials is carefully controlled to ensure that only suitable concrete is processed. Any other inclusions will result in the materials being classified as C&DW. The materials should also be used as soon as possible after crushing to gain maximum benefit from the available stabilization effect within the material, which is released during the crushing process. If the material is crushed and stockpiled, water accessing the exposed surfaces and fines will result in carbonation of the alkaline components and a loss of the potential cementing action.

Care should be taken when chemically stabilizing recycled concrete, as the combined effects of the incipient cement and the added stabilizer may result in "over stabilization" with excessive strengths and unacceptable shrinkage and cracking.

In terms of the necessary specifications, conventional (i.e. according to existing standard specifications) strength and grading requirements should be fulfilled, as well as normal CBR tests. Soaking of the CBR specimens will initiate some cementation but this will normally be mobilized during construction. The use of the final strength after long-term curing is in fact a "bonus" and should not be included in the design strength, as this is often not available during the critical early life of the road.

Careful interpretation of the test results from crushed concrete in terms of existing specifications is necessary. It is more than likely that modified specifications will be required, for instance to limit deleterious components or to take account of the unique cementation properties of the materials.

5.3 Pulverized fuel ash (PFA or fly ash)

Fly ash has been used as a construction material in roads for many decades in order to dispose of this particularly troublesome material. Its low density requires large areas for its disposal, and fine nature allows it to be dispersed by wind causing environmental problems. Fly ash consists primarily of silica and alumina with lesser quantities of iron, calcium and other elements, together with fine unburnt coal. However, in modern plants the efficiency is such that the unburnt coal is minimal. High quantities (> 5%) could have an interfering action on any possible pozzolanic reactions.

Fly ash has been used, in conjunction with lime or cement, as a soil stabilizer and also as a bulk fill material in embankments, and as a blend with soils in lower structural layers in roads. It can also be used as a layer material when treated with an activator to trigger any residual pozzolanicity.

Various forms of fly ash are available. These include fresh fly ash collected from the electrostatic precipitators, which is usually the most reactive (high pozzolanic component) and tends to be sought after by cement manufacturers for use as a cement extender. If this is not collected separately, it is usually added to water and the resulting slurry is deposited in ponds as "pond ash". This has the effect of reducing the potential pozzolanic activity of the ash. In addition, the bottom ash from the boilers is often combined with the fly ash and dumped as pond ash.

In terms of potential uses for fly ash, the fresh material can be combined with a small amount of lime and used as a soil stabilizer (the well-known lime-fly ash combination, widely used internationally for many decades). The pond ash would normally be used as a bulk fill for embankments. Theoretically, however, the pond ash, if blended with an adequate quantity of lime, should also react as a stabilization material. Research on each ash is required to identify the optimum trigger quantity of the ash with different materials.

When fly ash is blended with lime (or cement, but lime is usually considered the first choice), the high pH increases the solubility of the silica and alumina (Figure 3). Once this is in solution, it will react with calcium to form calcium silicates and aluminates, the primary cementing materials in Portland cement. Research needs to be carried out on selected Indian ashes to determine the optimum lime and fly ash contents necessary to treat various locally available materials, as sources are numerous and widespread throughout India.

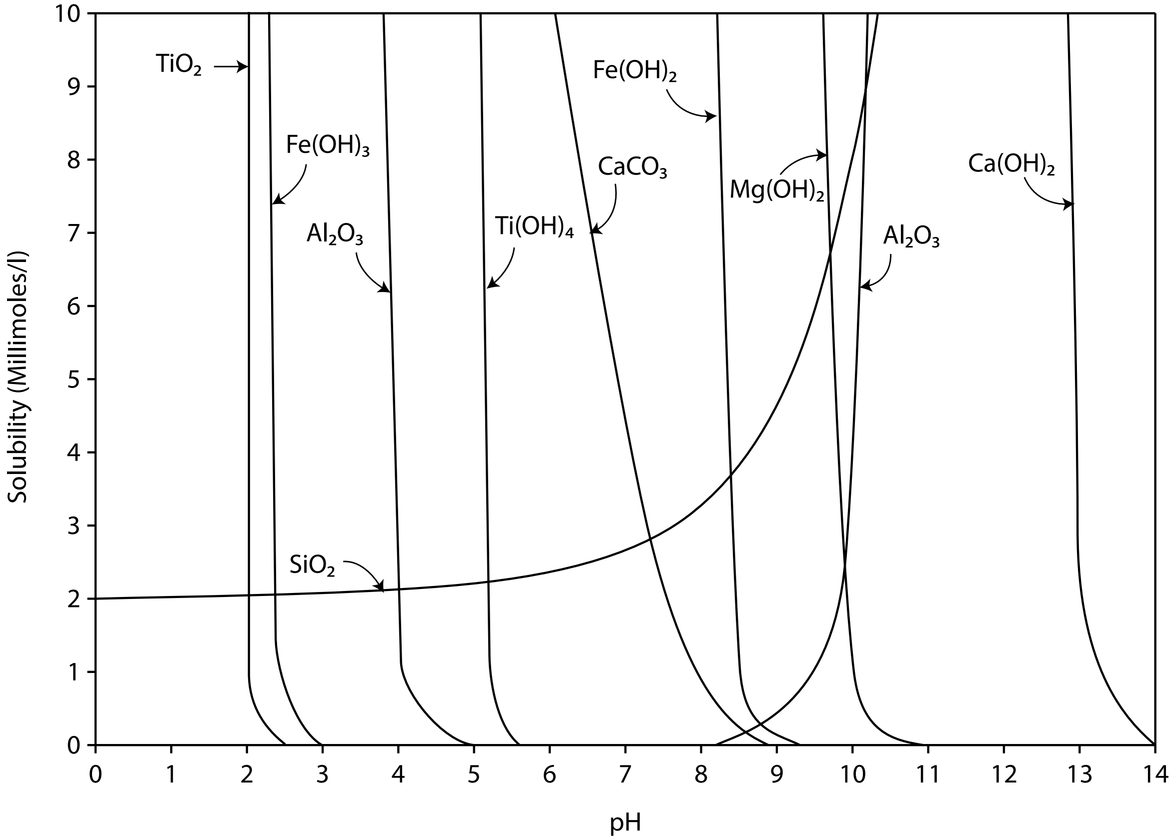
The fine nature of fly ash mostly excludes its use as a conventional construction material in terms of conventional specifications. Special conditions would need to be attached to any project specification involving the possible use of fly ash. Other possibilities are the use of combinations of fly ash with ground granulated blast-furnace slag (GGBS) both as stabilizers and possible bulk construction materials.

5.4 Blast-furnace slag

Blast-furnace slag is a by-product of the production of iron. In the production of iron, the raw iron ore (usually a mixture of iron oxides with some silica and aluminum in the form of quartz, feldspar and clays) is mixed with a calcareous material as a flux (usually limestone or dolomite) and coal, and heated in a blast-furnace. The molten iron ore separates out to the bottom of the furnace with the slag "floating" on top. This is periodically tapped off and sent for disposal. The quantity of slag produced depends on the composition of the materials smelted and can vary from one half to double the mass of iron produced. Similarly, the composition of the slag will depend on the raw materials utilized.

Disposal can be either in the form of tipping the molten slag onto dumps where it cools slowly into a single mass (air-cooled), or by granulating it – done by quenching it in water to cool it. Slag consists mostly of calcium

Figure 3: Solubility of various elements related to pH



compounds produced by the reaction between the flux and the silica, alumina and iron oxides. It is interesting to note that these are essentially the materials used to manufacture and the components of cement. However, all of the constituents are natural materials (rocks) and are thus highly variable in composition, resulting in a wide range of slag compositions. This variation is larger between different plants than within a single plant, which usually obtains its materials from constant sources.

The granulated blast-furnace slag is a fine sandy material that is mostly used in the cement industry as an extender after grinding, where it has a high economic value. The poured slag is typically used in construction and this requires breaking, crushing and screening before use. This process does, however, provide the opportunity to prepare materials to the required grading.

The current specifications permit (and, in fact, promote for rural roads) the use of slags, which conform to normal requirements. However, one of the main problems associated with the use of slag is the presence of un-hydrated oxides of calcium and magnesium, and the possible presence of sulphur compounds. The un-hydrated oxides will hydrate in the pavement layer with large increases in volume (between 190 and 220%). This can have severe consequences on compacted layers that include un-hydrated oxides. Planned and complete conditioning of the slag during processing, however, can eliminate these problems. A modified specification taking this into account is necessary for widespread use of the material.

The presence of sulphates, usually as a result of the combustion of the coal, could also have an effect on bituminous/asphalt surfacing. Again, if the potential problem is identified in advance, precautions can be taken to avoid any problems. International specifications to avoid the use of unacceptable slag have been developed and could be adapted for use in India. Many standard specifications allow the use of slag in road structural layers, where the traditional properties (grading, strength, etc.) are controlled.

5.5 Steel slag

Steel is widely produced internationally by introducing large volumes of air (sometimes pure oxygen) into a furnace containing iron to reduce the carbon, silica, sulphur, phosphorous and manganese content of the iron. The slags produced in these Basic Oxygen Furnaces (BOF) differ somewhat from the ordinary blast-furnace slags but are similar to Electric Arc Furnaces (EAF) slags. Hot iron and/or scrap metal are used to make steel, with lime (usually pre-calcined dolomite) added as a fluxing agent to reduce the melting point of the steel and assist with the removal of the impurities, by incorporating them in the slag.

BOF slags are generally more reactive with soils than ordinary blast-furnace slags and, after crushing, have been used in combination with certain soils to produce what is effectively a stabilized layer. Work done in Brazil by the Indian-based company Arcelor Mittal, in fact leads the world in this field, and should be extended for implementation in India. The process developed in Brazil (Acerita® and Revsol) has been licensed by Arcelor Mittal and should thus not be a problem to implement in India.

When used as a rock aggregate substitute (i.e. not relying on a self-stabilization action), similar problems that occur in blast-furnace slags can be expected from BOF slags, and their treatment/conditioning should be aimed at reducing un-hydrated oxides before use. Standard tests are available to ensure that the expansion has been reduced to acceptable limits, and conventional specifications in terms of strength, grading, etc. should be directly applied to such slags.

Research into the use of BOF slags, both as a processed gravel material and as a stabilization material when blended with clayey soils should be carried out in areas where the slag is readily available.

5.6 Other metallurgical slags (e.g. chrome, manganese, copper, zinc, etc.)

Slags are produced during the smelting of nearly all metals, each of which has its own properties and characteristics. However, they have all been "manufactured" at high temperatures with the addition of a fluxing agent, and are generally all reactive and contain un-hydrated oxides.

The use of any such slag (zinc, copper, manganese, chrome, titanium, lead, etc.) is possible as a replacement for natural rock in road construction, and in many cases can produce a more effective product. Their use in roads would be generally similar, because of their unique but potentially variable properties and compositions. However, each slag needs to be investigated separately to determine its specific requirements for processing and use, and any potential problems that may be associated with it. Because of the high burning temperatures, it can be expected that all slags contain un-hydrated oxides that may or may not expand on hydration if used in roads without suitable conditioning prior to use.

One of the main requirements with slags is to check their pollution potential in terms of hazardous or toxic elements (e.g. chrome [VI]). Only after a slag has been identified as a non-hazardous waste, should any research into its use in roads be initiated. Should a slag contain noxious or toxic components, it may be possible to remove them for use. However, this should not be carried out as part of any road investigation: it should be left to specialists in remedial treatment.

It should be remembered that, depending on the way it is used in a road, a by-product material will generally contribute very little to pollution of the surroundings. The quantity of slag used in layer materials (large quantities could be used in embankments and fills) is generally small in comparison to the surrounding areas. The potential for leaching of undesirable substances into the environment and dilution of this in rain, river or groundwater in most cases is not a problem.

As is the case with the iron and steel slags, any slag material that complies with the standard specifications (national standards), as well as with a test to ensure that the potential for excessive expansion is limited, can be safely used in structural layers in roads.

5.7 Aluminum industry wastes

India is now one of the world's largest producers of aluminum. The production of aluminum results in a number of waste materials, the two most common ones being bauxite residue and general landfill waste. The latter includes substantial volumes of spent pot linings.

Bauxite residue is mostly a "sand and mud (almost in equal parts) slurry that contains most of the iron and silicon impurities from the bauxite along with some residual caustic soda" (Wikipedia, 2016). With the caustic soda, this material is potentially likely to react well with certain soils to act as a stabilizer. Little research in this area appears to have been carried out, and even less with respect to its use in roads appears to be available internationally.

Its fine nature indicates that it is unlikely to comply with existing road material standards. However, its alkalinity may be potentially useful. Because of its widespread prevalence through India, research into potential uses of this material should be initiated.

5.8 Colliery spoil

The mining of coal results in vast quantities of waste material being stockpiled in these areas. These materials usually consist of a mixture of shale, carbonaceous shale, low grade (reject) coal, sandstone and any other materials that may occur in the coal mine. One of the biggest problems is that pyrite (FeS_2) and other sulphide minerals are common constituents of these colliery wastes. These oxidize in the heaps and get leached into groundwater, resulting in strong acid water conditions. The only way to mitigate such water pollution is to dispose of the dumps, many of which have been in existence for many decades. It is not possible to retro-fit appropriate drainage measures to such large dumps.

The use of materials from such dumps is currently difficult. Typically, there is no sorting of any material on the dumps. There is thus a highly variable mixture of shale, sandstone, unburnt carboniferous shale and poor quality coal, as well as carboniferous shale and poor quality coal that has spontaneously combusted and has become burnt.

All of these materials have different properties and the overall properties of any blend of such materials will probably depend on the poorest quality material in the blend and its proportion. However, there is often no reason why such materials should not be used for filling, and to improve the quality of very poor sub-grade materials by blending.

Experimentation with crushing of representative samples of the material to determine the "typical" properties in relation to current materials standards should be carried out where the materials are available. It is anticipated that such materials will be of at least sub-base standard in most cases.

5.9 Construction and Demolition Waste (C&DW)

India has large resources of crushed demolition waste growing in volume daily. An article in the Hindustan Times[1] indicated that Delhi produces about 4,000 tonnes of C&DW per day, making up about 40% of the total municipal waste. Of this only about 500 tonnes is prepared for recycling. This may be compared with Singapore, where about 98% of its C&DW is recycled, and the United Kingdom where about 280 m illion tonnes of C&DW are used annually (about 28% of generated waste). The Delhi Government has recently made the use of C&DW in all of its buildings and road projects mandatory. However, this will require the rapid development of recycling plants.

The potential for the use of C&DW in India is enormous. With the massive urban areas in nearly all states, the rapidly developing economy and the need for improved infrastructure, all of the possibilities are in place to maximize the benefits of using C&DW. However, the need for a better understanding of the properties and behavior of the materials is urgently required.

One of the first issues that needs addressing is the preparation of the material, in order to eliminate excessive "foreign" debris and ensure a relatively uniform material. The products from the existing plant in Delhi (Burari) plus the proposed 4 new ones (Tikri Kalan, Libaspur, Nizamuddin Bridge and Shastri Park) should be closely monitored to determine the optimum set-up and process. This can be extended to other major cities initially and then implemented on a wider scale.

A major benefit of using C&DW is that it creates significant employment in locating, procuring and transporting the material, as well as on site, for removal of foreign objects from the material before crushing. The potential for establishing such collection operations should be investigated. This will also assist in removing sources of environmental pollution in many city areas.

If laboratory testing of C&DW shows that it meets the specified material and/or aggregate strengths in the local material standards, then it can be used directly in roads, provided that all deleterious materials (wood and plastic) are removed. The materials will generally have no or very little plasticity, and gradings that are the result of the crushing process. They would usually have fairly continuously graded and possibly some reactive fines, depending on the age and source of the materials. Well-graded materials, even if these contain softer particles, will usually perform well if they are properly compacted.

5.10 Mine and stone-processing waste (marble, slate, granite, etc.)

Many parts of India have extensive quarrying and mining operations. These include conventional mine wastes (overburden and non-ore-bearing rock), unsuitable material (broken blocks in the dimension stone industry) and waste materials from the shaping and trimming of dimension stone. Other than the colliery spoil discussed in Section 5.8, the materials are mostly durable, of adequate strength for crushing and suitable for most pavement layers.

Surprisingly little research into the processing and use of these materials appears to have been carried out in India. It should be remembered that in many countries (UK, Europe, USA, the Middle East), limestone and marble are the dominant construction material. The only additional requirement for using these materials in India would be to optimize the crushing and preparation processes for local use.

The availability of portable crushing pants is increasing rapidly. These plants are able to make use of various crusher systems, which can produce almost any required grading and particle shape required.

1 07 December 2015

Marble slurry has been used in India, as fine material (generally all finer than 75µm) used as an additive to local materials. This material has little strength on its own, no genuine plasticity and no chemical reactivity, and thus should only be added to coarser materials which require fines to improve their grading. It is unlikely that any other benefit can be obtained from this marble slurry. Burning of the material, however, at temperatures higher than 1000ºC would produce a highly reactive calcitic or dolomitic lime very useful for stabilization.

Mine wastes are usually un-weathered or at worst slightly weathered rocks, and thus can be considered as high quality aggregates after processing. Plasticities are generally very low, aggregate strengths are high and the materials are usually durable. Standard specifications can then be used for their selection and use.

5.11 Phosphogypsum

A by-product of the fertilizer and explosives industry is phosphogypsum. This is a relatively pure hydrated calcium sulphate (gypsum ($CaSO_4 . 2H_2O$)) occurring as a fine powder. It has many uses from fertilizer to flowable fill, but has been used widely in certain states in the United States as pavement materials. Typically, it is stabilized with cement as a pavement layer. Despite the theory indicating that cement and gypsum react deleteriously, the combination when used in ratios of about 92-94% phosphogypsum to 6 or 8% cement has been shown to give no swelling problems.

The use of this material in combination with local soils and cements in India should be investigated, as it is generally a problem material to dispose of at source and can substitute large quantities of natural materials.

Phosphogypsum does not comply with any standard specifications for pavement layers, but should certainly be considered for use in areas where it is produced. Normal strength testing (Unconfined Compressive Strength) with various percentages of cement (preferably pozzulana cement) should be carried out to determine its suitability for use.

5.12 Tires

Millions of vehicle tires are disposed of daily around the world. There is a general consensus that their disposal is an ecological and environmental problem, with many landfill sites refusing to accept scrap tires. In the modern era, tires are manufactured using both natural and synthetic rubber, the latter being a by-product of the petro-chemical industry. Smaller and passenger tires tend to include more synthetic rubber than larger truck and earth-moving vehicles, while aviation tires are almost totally natural rubber.

The main use of recycled rubber in roads currently is in the form of finely crumbed rubber that is digested in bitumen to improve, among other properties, the elastic properties of the bitumen. This, however, only makes use of a small proportion of the total number of tires scrapped each year. Natural rubber, in general, is superior to synthetic rubber when used as a bitumen modifier.

Bitumen rubber can be used in normal bitumen applications as well as in crack sealing compounds.

General rubber waste (usually provided as chunks or chips) has been used widely in the northern states of the USA and in Canada as an aggregate in fills and embankments. It has good drainage properties, is lightweight in relation to conventional aggregate, and is also a good thermal insulator (against freezing of the upper pavement layers).

Rubber tires (in their whole form) have also been widely used to stabilize small slopes and reinforce fills and embankments. They can also facilitate the compaction of unstable soils (sands and coarse silts), which tend to move around under rollers, by using the tires to "confine' the materials during compaction.

Although rubber is highly elastic, compared with conventional construction materials, the potential for its use when shredded or chipped should not be overlooked, especially as a source of coarser "aggregate" for improving fine clayey and silty materials. Innovations in the pavement structure and surfacing may be necessary to account for its elastic properties.

5.13 China clay sand

During the production of China clay for the ceramic, pottery and various other industries (soap, paint, etc.), the fine clay material is washed from the source material leaving a mixture composed mostly of sand but including gravel, cobbles and boulders. This material, although continually produced (live feed), has resulted in large dumps at the sources of the china clay. These have accumulated over time and are usually available at no cost for use in roads.

As the properties of these materials depend almost entirely on the source materials, each material needs to be assessed in terms of the prevailing standard specifications for different uses in roads, in order to determine what can be used and in which layers. The materials are essentially natural gravels, and so need to comply with the standard specifications or any modifications made to them for low volume roads. No modifications to the standard material specifications or test methods are necessary. However, as many of these materials consist primarily of quartzitic material, they can be considered to be inert and durable and, as long as the required strength is provided, acceptable for use.

5.14 Foundry sand

In the casting of metal products (mostly ferrous but including aluminum, copper, etc.), molds and central cores are manufactured from a special type of sand which can be molded to retain the required shape when it is mixed with small quantities of bentonite clay, pulverized coal and water. It is heated to a high temperature when the molten metal flows into it, at which point the coal is combusted, the water is boiled off and the clay properties of the bentonite are lost. Once the items have been cast, the mold is removed to expose the product. The casting sand is reused as far as possible, but even so, about 5-7% is wasted each year, resulting in millions of tonnes of stockpiled waste sand.

This wasted material is usually blended with other waste products at the foundry (e.g. baghouse dust, floor sweepings and any other wastes produced). Like most other by-product materials, the composition of foundry sands can be expected to be rather variable, and each source would need to be looked at individually for use. However, the high temperatures involved in the casting process make the majority of the sands inert, with very little pollution potential. Typically, only the iron content is above most environmentally acceptable limits.

The addition of foundry sands to clays and silts (instead of conventional "sand stabilization" using a non-green natural material) should be investigated when such materials are locally available.

5.15 Crushed waste brick

Almost everywhere that one travels in India, the characteristic chimneys identify the presence of brick kilns. There are estimated to be about 140,000 such enterprises in India producing about 250 billion bricks per annum. The majority of kilns are Fixed Chimney Bull's Trench Kilns (FCBTK). During brick production, various problems may result in bricks becoming fused together and losing their shape, collapsing and losing their shape or being under- or possibly over-burnt. These bricks are normally wasted on the site. Observations at most brick kilns indicate large sources of such material, often mixed with the ash from the coal used to fire the kilns. Assuming that 0.1% of bricks produced are rejected (a conservative estimate – probably closer to 1%), it would mean that about 250 million bricks a year are rejected for conventional use in India. This is equivalent to about 1.125 million tonnes of reject brick per year. This would be sufficient material to construct 2,150 km of 150 mm thick pavement layer per year. In addition to the annual production, many kilns have large deposits built up over the past decades.

Many of the rural roads are brick-soled and have performed well. It is not certain whether the bricks used in these roads are normal commercial quality or reject bricks. Many of the visible bricks seemed to have been malformed, although the majority appeared to be normal bricks.

It is recommended that research be done on the brick dumps at a number of kilns to assess the properties of the crushed bricks ("brick-bat"). Crushing could be done manually or using small jaw crushers. It is anticipated that the softer bricks will shatter and produce mostly fine dust and silt, while the harder bricks will fracture into an aggregate. With a little screening (manual in most cases initially), the softer components would be removed. The strength of the broken brick material (i.e. CBR) and brick aggregate (AIV) would indicate the potential of this process for producing crushed aggregate for roads. Even if the crushed bricks are too weak for base course aggregate, they would certainly be useful to blend with *in situ* sub-grade materials (fractions passing 20 mm) to boost their strength. Preliminary investigations have been carried out at the Central Road Research Institute (CRRI) Delhi, but considerably more work is required to be done to develop standards for the preparation and use of these materials.

Inspection of a brickyard indicated extensive "dumps" of unburnt, over-burnt and deformed bricks as well as piles of the residual ash produced from the coal burning process. The latter material is a non-plastic sandy gravel. Combinations of these two materials, after breaking down the bricks, to pass about 20 or 25 mm, would be extremely useful in improving weak clayey sub-grade materials as well as producing a material that would probably suffice for sub-base layers in many situations. The reject bricks are often combined with the ash produced during their firing, which in itself may have some pozzolanic potential. Even if it does not, the ash is a neutral, inert material that would have no detrimental impact on the reject brick usage.

5.16 Used rail ballast

Rail ballast is "manufactured" from a high quality, durable crushed stone aggregate with a particle size typically in the range of 26 to 75 mm, depending on the loads on the rolling stock using the lines. This material is subject to extensive abrasion during loading, which generates fine materials that need to be cleaned from the ballast regularly. However, after a certain number of cleanings, the ballast tends to become rounded, reducing its frictional properties, and must be replaced.

The ballast that is replaced should be considered for use in roads. Although the material has become rounded, it is usually still adequately strong and durable for recycling as a road aggregate. Because of its large size, relative to road material, and the large volumes that are disposed of (500 to 800 m^3/km of single track), it can be crushed to a nominal 20 or 30 mm graded aggregate for use in roads. Sometimes, the ballast becomes so clogged with fines (fouled) that it needs to be replaced, even before it has become rounded – this too, including the fines, can be processed for use in roads.

Little research in this area has been carried out, and it is suggested that this avenue of recycling materials be followed, particularly in terms of the extensive environmental benefits that would follow. These would accrue from both the reduction in use of natural materials as well as a reduction in the disposal requirements of the used ballast, often discarded along the railway lines.

5.17 Furnace and incinerator bottom ash

It is not uncommon in modern times for material disposed of in landfills in or near urban areas to be incinerated, in order to minimize the landfill space requirements. The incineration process is often combined with energy generation, utilizing the heat produced from the incineration to power energy turbines. The process, however, has not been without problems, as a result of the pollution and toxic gases produced during the incineration of a wide range of mostly domestic refuse. Often this also includes wastes produced by local small-industries in the urban areas.

It has been identified that low cost incinerators as are currently being used in India, emit considerably higher volumes of toxic fumes than the more efficient, but costlier, incinerators used for instance in Europe.[2] There is, however, always a trade-off between these fumes and the methane and carbon dioxide produced during the decay of organic waste in the landfills.

The ash produced by such incineration of landfill waste is similar to any other cinder ash (produced by burning coal for instance) and would have similar properties and problems. As this form of waste disposal is likely to increase in future due to the dearth of suitable landfill space and other environmental concerns in urban areas, serious consideration should be given to investigating this material for use in roads.

5.18 Cement Kiln Dust (CKD)

Cement kiln dust is a fine by-product of cement production. It is found in the exhaust gases released from cement kilns during the production of Portland cement clinker, and is collected by fabric filters or electrostatic precipitators. Kiln dust has exactly the same constituents as Portland cement: lime, silica, and metal oxides, but in extremely fine particle sizes.

This material contains reactive calcium oxide, the proportion depending on the location within the dust collection system, the type of operation, the dust collection facility, and the type of fuel used.

Because of its fineness, CKD has been shown to decrease initial and final setting times, which could be problematic in road construction, where significant time is often required for the placing, mixing, compaction and finishing of road layers. Rapid setting of stabilizers is usually a problem in this area, with the material "setting up" before the construction process is complete, leading to degradation of the layer as a result of attempting to achieve the specified densities and final shape.

However, blends of CKD with perhaps fly ash or pond ash should be investigated for use as stabilizers.

5.19 Glass

Broken glass has been used in the construction of roads in the United Sates, New Zealand and Canada for many decades. It is a high quality material and should preferably be recycled as glass. However, in general, colored glass is not recycled, and this is where most of the glass used in roads originates. It is a stable, inert, non-toxic material that lends itself perfectly to a road construction material.

2 Ferris, 03 December 2013, "Out of India's trash heaps, a controversy on incineration"

The main use of glass up to now has been as a fine aggregate (up to 6.7 mm) in asphalt. Collecting and processing this waste glass has cost implications that often raise its cost to almost that of conventional aggregate. Crushed glass is, however, a processed material that contains embodied energy, and there are worthwhile sustainability benefits obtained by making more use of it. Increased use would be based on the outcome of new research. Because of its highly brittle nature, it is probably unlikely that glass could be used as a general aggregate, where it is not bedded into a semi-ductile or plastic material.

In addition, by limiting the fines content, crushed glass would make an excellent filter or drainage material, because of its good durability and resistance to degradation. However, in the presence of highly alkaline materials or fluids, the solubility decreases significantly. This would need to be considered if any chemical stabilization or concrete work was involved in surrounding materials.

5.20 Spent oil shale

Spent oil shale is a solid residue from the process of extracting synthetic shale oil from oil shale. Oil shales are organic rich sedimentary rocks (not necessarily complying with the strict definition of shale) comprising an inorganic matrix (clays and silts), bitumen and kerogen. A synthetic oil is extracted from the shale by heating it to between 450 and 500°C. The remaining "baked shale" is a hard dense rock, although it may still have a high carbon content, the residue of kerogen after losing the oil/gas.

The processing of oil shale by heating is only economical when the deposits are at the surface.

It is a potentially valuable engineering material when present in adequate quantities, and can be used as general embankment fill or on lower selected layers in roads. However, it is a relatively high quality material which makes it more suitable for use as selected materials for sub-base or even base on low volume roads.

Spent oil shale is, however, classified as a hazardous waste by the European Union.

5.21 Summary

The Indian literature indicates numerous short articles and review papers on the use of a wide range of by-product materials, but little seems to have been compiled into a meaningful volume for using these materials in roads in India. It is interesting to note the number of research articles emanating from India on a wide range of by-product materials. However, these seem to be mostly based on short studies carried out by research students at universities, which do not follow through to the development of wide-ranging specifications and user guidelines.

By-product materials (on their own or in combination with other materials) are eminently suitable for use in roads, as different layers within pavement structures all require materials of different properties. There will thus almost always be some type of by-product material suitable for a specific layer. The use of by-products for the stabilization or improvement of poor quality materials such as alluvial silts, which are associated with many of the large rivers in India, and black clays (cotton soils) so widespread through India, require intensive investigation. This needs to be done on project by project basis, depending on the local soil materials and the availability of by-product materials.

A concerted drive through research institutes and universities in India should be initiated in order to develop techniques for processing and utilizing the wide range of by-product materials in India. As the population and urbanization increases, the availability of conventional construction materials is likely to diminish considerably, and alternative, preferably "green", materials will need to be utilized in road construction. In order to satisfy the growing need for materials, research and development should be initiated as soon as possible.

A summary of the potential waste materials, classified by their locations and including highlights regarding their potential uses and problems is shown in Table 1. The need for additional research is probably common to most of these products and is not identified individually in the Table.

TABLE 1: CLASSIFICATION AND SUMMARY OF USES AND PROPERTIES OF BY-PRODUCT MATERIALS

Classification of by-product material	Possible uses	Potential problems	Special requirements
Urban by-products			
Crushed concrete	• Base • Sub-base • Concrete aggregate	• Can lead to over-stabilization	• Requires careful sorting at collection point • Requires crushing and screening
Aluminum industry wastes	• Below sub-base • Stabilizer	• Very fine material • Often mixed with other wastes	• Unknown at this stage
Construction and demolition waste	• Base • Sub-base • Concrete aggregate	• Requires careful processing/ sorting • May contain a lot of deleterious materials	• None – should behave as a normal aggregate
Tires	• Below sub-base • Bitumen modifier • Concrete aggregate	• Variability of rubber types in tires (natural and synthetic)	• Requires innovative research (e.g. highly flexible pavements) • Collection, sorting and processing must be formalized
Foundry sand	• Sub-base • Below sub-base • Mechanical stabilizer	• Fine grained • May contain unusual chemicals (release agents`)	• Unknown at this stage
Cement kiln dust	• Stabilizer	• Very fine dusty material • Pozzolanicity lost with storage	• More rapid construction (quicker reaction rates due to fineness) • Difficult to place and mix
Glass	• Surfacing aggregate • Mechanical stabilizer	• Difficult to work with • Fractures into flaky particles	• Special processing/crushing technique needs to be developed
Rural by-products			
Pulverized fuel ash (PFA or fly ash)	• Cemented layer • Stabilizer	• Very fine/dusty • Monopolies often control supply	• New innovative uses need to be assessed
Blast-furnace slag	• Surfacing aggregate • Base • Sub-base • Concrete aggregate	• Contains unhydrated oxides • Can be variable • Possible deleterious components • Variable density (voids)	• Must be conditioned before use to eliminate oxide

Classification of by-product material	Possible uses	Potential problems	Special requirements
Steel slag	• Surfacing aggregate • Base • Sub-base • Concrete aggregate	• Contains unhydrated oxides • Can be variable • Possible deleterious components • Variable density (voids)	• Must be conditioned before use to eliminate oxides • Otherwise similar to a conventional aggregate
Other metallurgical slags	• Base • Sub-base	• Contains unhydrated oxides • Can be variable • Possible deleterious components • Variable density (voids)	• Must be conditioned before use to eliminate oxides
Colliery spoil	• Sub-base • Below sub-base	• Highly variable materials • May contain sulphates • Abrasive on crushing plant	• Needs good sorting and processing • Otherwise similar to a conventional aggregate
Mine and stone processing waste	• Surfacing aggregate • Base • Sub-base • Concrete aggregate	• May contain deleterious materials	• Need to be assessed individually
Crushed waste brick	• Sub-base • Mechanical stabilizer	• Variable physical properties • Small individual deposits	• Needs investigation for each use
Furnace bottom ash	• Base • Sub-base • Below sub-base	• Soft particles • Contains unburnt coal • May contain sulfates	• Needs careful processing
Spent oil shale	• Sub-base • Below sub-base	• Variable hardness and composition	• Little known
By-products from both rural and urban environments			
Reclaimed bituminous material (RA)	• Asphalt • Base • Sub-base	• Variable materials	• Each source needs evaluation and investigation for each project
Phosphogypsum	• Cemented layer	• Very fine powder • Changes moisture condition readily	• Needs additional research for bulk use
China clay sand	• Mechanical stabilizer • Below sub-base	• Fine grained	• Little research done
Used rail ballast	• Base • Sub-base • Concrete aggregate	• Collection of sufficient quantities	• New disposal strategy from railway authority required

6. Environmental and Sustainability Issues

6. Environmental and Sustainability Issues

"**Green**" issues are becoming increasingly important in the use of road construction materials. It is essential that sustainability issues and minimal environmental impacts are fully addressed.

Sustainability was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" by the Brundtland Commission in 1987. The use of rock and natural gravels in road construction is not a sustainable practice and already in some parts of the world, suitable road construction materials have been depleted, which does compromise the ability of future generations to construct roads in a similar manner to today's designs.

In addition, sustainability encompasses a holistic consideration of economic, social, and environmental progress with a long-term perspective, in both a present (intra-generational) and future (intergenerational) context.

Every quarry and borrow pit developed will have certain environmental impacts and will leave a scar on the landscape. Unlike the construction of a dam, where the borrow pits and quarries are usually located in the dam area such that they are flooded after filling of the dam, borrow pits developed for road materials will always leave evidence of their use, even with the best of rehabilitation works. Materials should thus be sourced as far as possible within the road reserve, cuttings developed for the road and side drain areas. This minimizes their aesthetic impact but is seldom possible for all of the materials required for the road structure.

In many countries, obtaining the required environmental approval can take many months or even years and is one of the main contributors to delaying projects and causing time overruns, with their associated increase in costs.

By using by-product materials that have been through an environmental acceptability procedure (checking for pollutants, hazardous and toxic components, etc.) and have been approved with a materials safety data sheet, significant time and cost savings can be achieved on projects. Added advantages of the use of by-product materials are that land that could be used for other purposes (depending on the nature of the waste stored on it) is released after using the by-product materials.

Investigations have shown that the potential for leaching of undesirable elements from by-product materials used in road layers is actually minimal, even compared with the pollution (dust, rubber, etc.) and undesirable elements (lead, chrome, sulphur, etc.) on the road surface. Movement of water in and out of the road structures is normally minimal compared with surface run-off.

The use of by-product materials often reduces the quantity of Greenhouse Gas Emissions (GHG) compared with conventional materials, which require significantly more processing, with concomitant exhaust emissions. A full study on each resource as compared with natural gravel or crushed rock alternatives needs to be carried out using one of the many GHG calculators available, to determine which of the alternative resources generates the least emissions. This should, however, not be used as the sole criterion for selecting a material, as other sustainability and technical issues may often be more important locally.

GHG determination is not only related to the materials but the entire construction and operation process. Each material used will have certain emissions attached to it, including the production and haulage of the material. Construction too, will have emissions related to the operation of the plant (for spreading, mixing, compaction, finishing and curing), provision of water (pumping and hauling), and asphalt production (binder production and delivery, heating and placing, etc.). These need to be determined for each project (or experiment) to determine the total emissions for comparative purposes.

7. International Review

7. International Review

Most countries have introduced recycling of many "waste products" as part of their environmental strategies, with emphasis on different issues in the different countries. However, a lot of the potential uses of such products in the road industry are still in the early stages of development, and are being incrementally included in projects as more information is gathered about their unique properties and usefulness.

7.1 Australia

Australia has developed a significant road network, serving a population that is highly concentrated around the perimeter of the country with a very low inland population density and generally low traffic volumes. Using conventional pavement designs and materials, this would not have been economically possible.

Although there are national materials and pavement design protocols in Australia, for many years each of the individual states has researched and experimented with local materials and conditions. Most states in fact have unique requirements for their roads, particularly the lighter trafficked roads that are important for connectivity of widely-spaced towns and villages. These optimize the use of local materials and environments.

Each state has unique materials that have required research and development to determine their individual properties and mechanisms for identifying and overcoming problems. This has frequently involved new test techniques and protocols, with specifications for specific materials even differing from state to state.

In the past, much of this work was carried out (or at least coordinated) by ARRB and the CSIRO, but more recently, local state roads departments and universities have been more involved in such investigations and development. The main criteria used are typically the plasticity and material strengths.

There is also a strong move in Australia towards the increased usage of waste materials in road construction, with institutions such as ARRB carrying out research in this area where funding is available.

7.2 Brazil

Brazil is a tropical country with widespread and deep deposits of laterite and typical red tropical soils. These are the most-cost effective and accessible materials in most areas, but seldom comply with the national specifications for road construction materials and aggregates.

National specifications have been modified for the use of laterites with a new range of tests being developed and specified, some of these being based on work carried out by LNEC (Portugal) during the 1960s in their African colonies of Mozambique and Angola.

Even then, the nature of the laterites differs widely across Brazil, with some areas having gravelly hardpan deposits, and other areas having fine sandy tropical soils with variable iron and aluminum contents. In such cases, specific test techniques and equipment have been developed for characterization and classification of these fine materials for use in roads.

Without interventions such as these, Brazil, which is a large country with a low per capita income, would never have been able to provide the road network of 1.6 million km that it now has, with more than 200,000 km being paved.

7.3 South Africa

Most low volume roads in South Africa are constructed to TRH 4 (1996) standards using the catalogue design method. The catalogues range from roads with cumulative standard axles of between 3,000 and 100,000,000 over their design lives, similar to the Indian LVR manual (IRC SP 72: 2014).

In 1987, a simple design method based on a massive investigation involving laboratory and Dynamic Cone Penetrometer (DCP) testing of existing roads (more than 1,000 sites) in the old Transvaal was developed. This was used as the basis for a national document on the appropriate design of low volume roads in 1992. Additional work carried out between 1989 and 1994, on more than 50 roads constructed using "marginal quality" local materials, thin pavement layers and reduced pavement layers, confirmed the suitability and appropriateness of these designs.

However, because of the local procurement methods and the fact that many of the consulting engineers were older and more conservative, these techniques were used only on a limited number of roads by a few of the more progressive engineers. However, great success was achieved allowing upgrading of lightly trafficked unpaved roads to appropriate paved roads where conventional methods would have been far too costly. This provided access to many areas that would not have had much more than poor unpaved roads.

7.4 United States

The United States is an extremely large country with a wide range of geological, climatic and topographical regions, each with its own specific challenges. The north eastern areas of the USA have been subject to extreme and widespread recent (< 1,000,000 years) glaciation, resulting in thick deposits of glacial tills (un-weathered low plasticity gravels) interspersed with shallow fresh rock outcrops. Most materials for low volume (and even unpaved) roads in these areas thus consist of crushed rock or processed tills. As one moves towards the south and west, more residual materials occur. In the deeper south, certain pedogenic materials are common (caliche, kankar or calcrete).

A number of national materials specifications for roads are used in the USA (e.g. AASHTO, Federal Highways, etc.). There is little differentiation in these between national highways and lower volume local access roads. Some states have investigated the use of local materials, with only small regional modifications to the typical specifications being incorporated. The main interest in low volume roads, however, is in private and state enterprises related to tourism, forestry and Native American reservation areas. However, even these developments allow minimal changes to the traditional specifications for very lightly trafficked roads.

Although work on low volume roads is increasing in the United States, it is considered that the approach being taken is probably incorrect. The process there is to work from the existing standards for high quality, high volume roads, expanding the material requirements where necessary and considered appropriate, for example, by increasing the permissible plasticity index from 6 to 8% for certain materials. This is considered to be the incorrect approach.

A more realistic approach would be to work from unpaved roads upwards, by utilizing the existing materials and adding local materials to satisfy performance-based criteria (strength and thicknesses) at the expected *in situ* environmental conditions. Thus, strengths measured with the DCP apparatus for example, can be used at any foreseeable moisture condition in which the road will be expected to perform.

7.5 Other countries

Over the years, limited funding has resulted in many countries such as Zimbabwe, Botswana, Ethiopia, Tanzania and Malawi implementing innovative pavement designs in order to expand their road networks. These include wider use of non-traditional construction materials and innovative material classification and designs.

There has, however, recently been a strong move in many African countries towards the use of more innovative materials and pavement designs based on the DCP method, which uses the DCP to classify materials both in the field and in the laboratory, for use in low volume roads. Manuals incorporating these techniques have been developed for Ethiopia, South Sudan, Malawi, Tanzania and Mozambique. Training in the techniques has recently been carried out in South Africa, Kenya, Democratic Republic of Congo and Ghana, among other countries.

8. Innovative Material Characterization Procedures

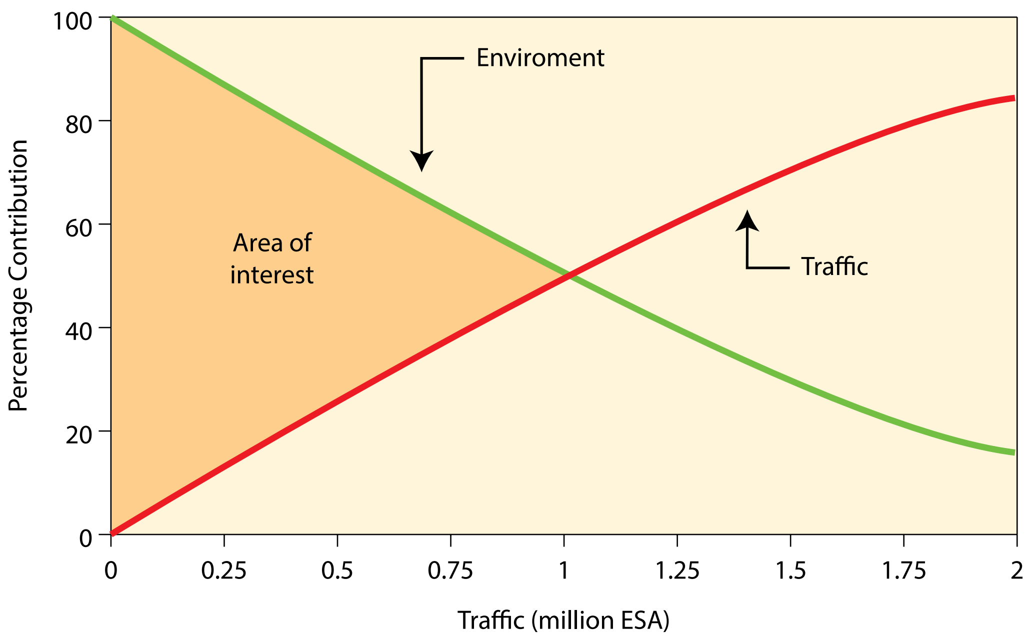
8. Innovative Material Characterization Procedures

The wider use of non-conventional and innovative materials often requires a conscious change from conventional testing and classification methods. This has been seen in countries that were successfully building low cost, lightly trafficked roads more than 3 or 4 decades ago, particularly Western Australia and Zimbabwe.

Both of these regions moved from conventional soaked CBR designs to the use of confined compressive strengths at the expected density and moisture regimes, as their primary design criteria for low volume roads. As discussed earlier, Brazil has the criteria necessary to classify material as a laterite (the silica-sesquioxide ratio), and then allows significantly reduced specifications for the use of such materials in low volume roads. They also make use of other special test methods such as petrifaction degree and Castro swell.

Recent research has shown that the performance of low volume roads (< 1 million cumulative equivalent standard axles) is more dependent on the environment than on the traffic (Figure 4). This important aspect is incorporated

Figure 4: Contribution of environment and traffic to performance of roads



into the "context-sensitive environmentally-optimized design (EOD) method" currently being introduced in India, which adapts the pavement design to the environmental (topography, moisture and sub-grade) conditions that occur along the road in order to optimize the pavement structure for each condition.

In South Africa, major problems were experienced with the use of the Karoo volcanic materials (basalts and dolerites), which are similar (although older – 160 million years compared with about 80 million) to the Deccan Trap basalts in India. The South African materials often have a presence of expansive smectite, leading to durability problems with the aggregate. Because of this, two specific tests and associated test limits – the Durability Mill Index test and the Modified Ethylene Glycol Durability test –have been developed to assist with early recognition of the problem. Use of these tests minimizes the risk of premature failure of the material.

It will be important that appropriate tests for both natural and by-product materials and suitable specification limits are developed for the Indian situation. However, the use of procedures such as the DCP design method minimize many of the material specification risks, as the actual required *in situ* material properties are utilized, and durability is thus the only parameter that needs to be assessed for selected materials.

The major hurdle, however, is to get buy-in from local road practitioners to actually implement the "innovative" procedures. The 15% innovation requirement of NRRDA discussed later in this report will certainly assist in this regard.

9. Improvement of Unsuitable Materials

9. Improvement of Unsuitable Materials

There are many cases when the local materials, even if highly compacted and retained in a dry state, do not meet the strength requirements for a specific layer. In these cases, the use of some form of mechanical or cementitious stabilization may be necessary. There are a number of options available for this, many of them, however, being expensive. A laboratory investigation to assess the improvement in material properties with each of the techniques is essential, in order to optimize the cost and the material properties. This usually requires innovative thinking and appropriate laboratory testing on the part of the engineer.

It is essential in this process that the following questions are answered:

- What are the pavement requirements?
- What materials are available for investigation?
- How best are each of these materials treated?
- What laboratory test procedure is necessary to prove their "fitness for purpose"?

9.1 Mechanical stabilization

This involves the improvement of a material by purely mechanical means. Various techniques are available for this, and must be seriously considered as they are far more cost-effective than chemical or other types of stabilization.

9.1.1 Compaction

Compaction is by far the most economic and simple way of improving a material. All the properties of a material are enhanced by achieving as high a degree of compaction as possible. These include:

- Higher shear strength and stiffness
- Lower permeability
- Less rutting potential
- A better support (anvil) for the compaction of overlying layers

All attempts to improve the compaction of layers and achieve the highest possible compaction should be made. This requires a good compaction plant with operating vibration capacity, a uniform distribution of moisture (at close to or just below optimum moisture content for modified compaction) through the material, and the necessary number of passes. Compaction is one of the cheapest construction activities and additional compaction generally involves only a small additional fuel cost. The plant and operators are on site anyway, even when the compaction process is not taking place, and thus involve no additional costs.

No compromise on compaction should be allowed, as the use of marginal materials and highly compacted sub-grades not only improves the pavement performance, but also allows thinner pavement layers to be used, with significant material savings and the associated sustainability benefits. Compaction to refusal, which normally entails a maximum of 4 or 5 additional roller passes until no additional densification occurs, but avoiding breakdown of particles and de-densification, is generally considered a highly beneficial operation. All attempts to improve the compaction of layers and achieve the highest possible compaction should be made. This requires a good compaction plant with operating vibration capacity, a uniform distribution of moisture (at close to or just below optimum moisture content for modified compaction) through the material, and the necessary number of passes.

9.1.2 Removal of oversize material

The removal of oversize material enhances the workability of the material as well as improving its properties. The presence of excessive oversize constituents often acts as "plums in a pudding", resulting in no strength being contributed by the aggregate (no inter-particle friction/interlock), with the strength of the finer matrix determining the overall material properties. In addition, the impact of the oversize material on the properties of the bulk material cannot be determined, as these aggregate particles are excluded from most testing.

There are many ways of removing oversize material, but this is done most economically at source where unnecessary haulage of the oversize material to the roads (and usually back to the borrow pit when not used) can be avoided. Screening and/or crushing in the borrow pit should be carried out when excessive oversize material is present. This

Figure 5: Grizzly with too wide a spacing and bars that are too weak

is usually classified as material with more than about 5 or 10% in excess of 37.5 mm. The use of "grizzly" screens is usually the most cost-effective means of screening oversize material, but it is important that the screens are well constructed and have the correct openings. An example of a large screen constructed with reinforcing bar that is too thin and can be deformed by large stones is shown in Figure 5.

The presence of oversize materials results in a poor finish of the compacted layer surface and makes mixing, compaction and final cutting of levels difficult. This is not critical for sub-grade and sub-base layers (in fact a rough surface may enhance the bond between the layers), but is not permissible for base courses where a thin bituminous surfacing is to be applied. Large aggregate particles also interfere with the uniform compaction of the materials (material adjacent to large particles is not effectively compacted).

9.1.3 Blending

Blending of different materials can be used to improve the characteristics of many poor materials. Mixing of materials from different sources, usually one coarse and one finer can reduce (or increase when required) plasticity and improve the shear strength and performance of many materials. The optimum blend ratio is usually determined by laboratory testing, but can also be estimated mathematically using various processes.

In India, the increased use of blending is perceived to be a major advantage in future construction of LVRs. Many of the natural sub-grades are very weak, fine materials (silts and clays) with no gravelly alternatives. Their strengths can be significantly improved by the controlled addition of coarser materials. These coarse materials can often be obtained from the by-product materials discussed previously, preferably materials in the range 5 to 25 mm in diameter. However, to optimize each possible blend, laboratory tests with different proportions of the two materials need to be carried out in order to identify the optimum blend ratio.

The addition of a coarse fraction will usually raise the quality of the silty/clayey material to at least selected sub-grade and often sub-base quality. In such cases, laboratory investigations are necessary using various proportions of the two materials to determine the optimum blend ratio (Figure 6).

This type of investigation is particularly relevant in parts of India, where there are often, for instance, large sources of reject bricks that could be broken/crushed and added to the local silty materials to provide a better material. Representative samples of the reject bricks (even including the residual ash and soft bricks) should be crushed to a maximum size of about 20 or 25 mm, and added in various proportions as indicated for the sands above, to determine whether the strength (in terms of DN value) can be improved to that required for the proposed layer.

Figure 6: Change in strength (DN in mm/blow) on addition of sand to marginal gravel materials

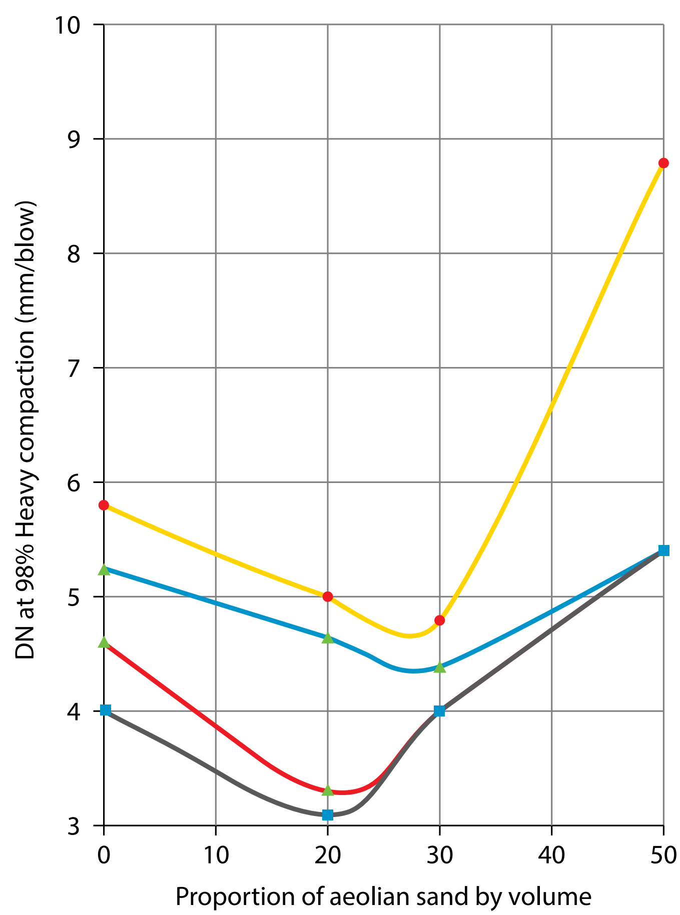
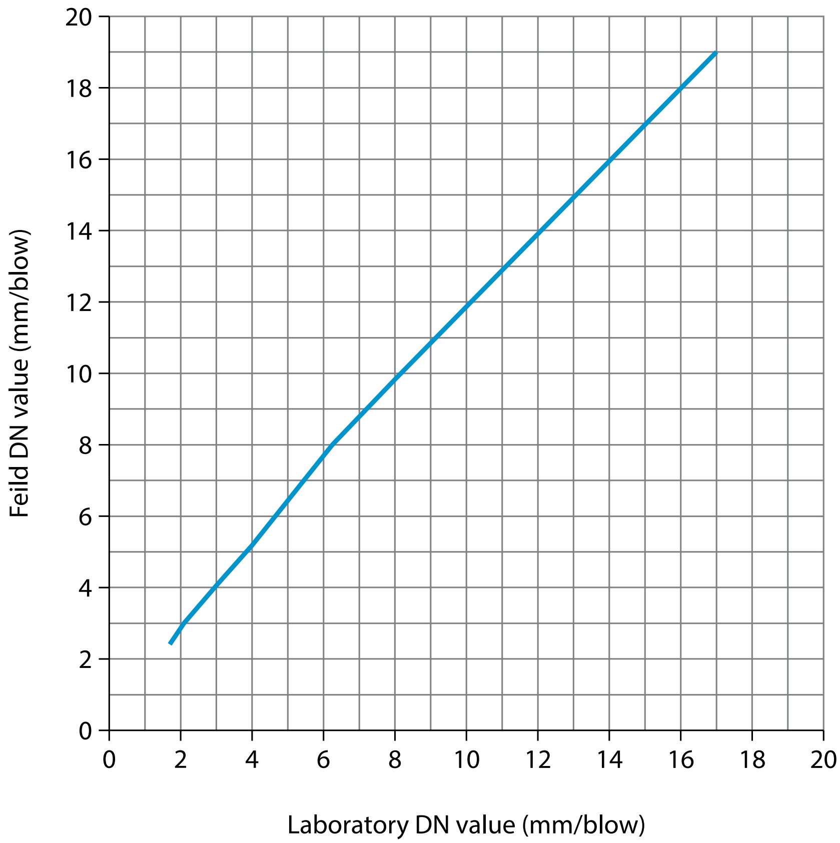


Figure 7: Conversion line from laboratory to field DN value



Various molds are prepared and tested in the laboratory with a DCP and the actual penetration rate determined. It is known that there is an effect of confinement in the laboratory, and the actual measured value should be corrected for the expected field value according to Figure 7.

9.2 Chemical stabilization

Chemical stabilization involves the addition of a chemical agent to the materials that affects the chemical properties of the material. This could be either chemical modification, in which only the actual minerals are affected without any chemical cementation (i.e. no tensile strength is developed), or cementation in which new cementitious bonds (hydrated calcium silicate minerals) are developed, imparting a significant tensile strength to the material.

The quantity of stabilizer required to achieve the desired properties may be so high as to make the process totally non cost-effective. For this reason, each material has to be assessed using the most suitable stabilizers, following a standard test protocol. This protocol will vary depending on the types of stabilizer investigated.

Conventional chemical stabilization makes use of cement, lime, lime/fly ash blends and various other mostly by-product materials (GGBS, cement kiln dust, burnt rice husk ash, etc.). Cement is typically used for materials with a plasticity index (PI) below about 10%, lime for materials with a PI greater than 15%, and combinations of the two with intermediate PI values. It should also be noted that cement can have a range of compositions, depending on the type and quantity of extender (i.e. PFA, GGBS, pozzolan, ground limestone, etc.) added, and the rate of reaction depends significantly on the fineness to which the cement is ground.

Once the best stabilizer type has been identified, it is necessary to determine the optimum stabilizer content. This requires that the material is tested with various contents of the selected stabilizer to determine the optimum content at which the strength (Unconfined Compressive Strength [UCS]) and (Ultimate Tensile Strength [UTS]) is obtained. It should be noted that, in order to ensure long-term durability of the cemented layer, this percentage of stabilizer should exceed the Initial Stabilizer Demand by at least 1%.

Chemical stabilization should not be seen as a purely mechanical process in which a fixed quantity of stabilizer is added to any material, as every material has unique mineralogy and properties. This results in different stabilizer requirements, both in terms of quantity and type of stabilizer. Testing of the Unconfined Compressive Strength (UCS) is essential to determine which stabilizer is best and what quantity should be added to produce the necessary properties. Adequate guidelines in this respect do not currently exist in India.

It is also essential that the specifications used are related to the test methods that they were developed from. Examples of a combination of modified test methods (combined with poor testing) and adapted specifications have been seen used in India, and problems regarding quality assurance were being experienced.

Chemical stabilization is an art, and champions in this art need to be developed in India. Many problems with chemical stabilization occur during construction and it is essential that a pool of experts be developed in India, who can respond to problems and quickly identify the mechanisms for avoiding them during projects, without undue disruption of progress on the project.

9.3 Bitumen stabilization

The use of bitumen to stabilize materials is becoming increasingly popular due to the modern equipment that facilitates this type of construction. Both bitumen emulsion and foamed bitumen are used, as these products produce a relatively flexible material with significant water resistance. However, bitumen is expensive compared with other stabilizers, and is usually used where specific material properties are required, often in the rehabilitation/recycling of existing failed pavements. This is only recommended for use in LVRs under exceptional circumstances and with proper engineering design by someone well experienced with bitumen stabilization.

9.4 Proprietary soil stabilizers

Internationally, the road construction market is currently flooded with various proprietary chemical soil stabilizers and improvers marketed by mostly non-technical people. These chemicals should be used with caution, only after rigorous laboratory testing, careful economic analysis and preferably carrying out some properly controlled and monitored field trials. The use of chemically treated layers near the top of the pavement structure, as proposed by many of the chemical vendors to use local materials, should ensure that the pavement balance is not disturbed too much.

Proprietary soil stabilizers make use of various physical and chemical additives, each with its own mechanisms, actions and results. Many of these are not communicated fully by the suppliers and it is often difficult to carry out tests to assess their performance.

Together with routine laboratory testing, the best way of monitoring the effectiveness of such chemicals is through trial/experimental sections. It is essential that the experiments are designed to test the specific properties of the products being experimented with, a proper control section is constructed (identical in all respects except for inclusion of the chemical) and the property being "tested" is regularly monitored. There is no other means of fully testing the effectiveness of proprietary chemical stabilizers.

9.5 Other innovations

India probably leads the world in terms of locally developed innovations and research in road construction. These include techniques such as jute, coir and coir mat soil reinforcement, the use of recycled plastic bags in hot-mix asphalt preparation, the use of burnt rice husk ash as a pozzolanic stabilizer, etc. Unfortunately, many of these are not taken to the full implementation stage with specifications and methods that will allow their confident use.

Experiments conducted using some of these technologies were mostly not constructed or monitored adequately to obtain sufficient useful data to facilitate full-scale implementation of the technologies. The other problem is that some of the properties cannot be determined in a short period (less than probably about 5 years). Accelerated testing may assist in getting certain early results regarding structural performance, but will not assist in determining, for example, durability of potentially bio-degradable products such as coir or jute. The impact of such degradation on the structural performance would only be measureable after the materials have decomposed.

Discussions with local field staff regarding the use of burnt rice husk ash for stabilization indicated that although large quantities of rice husks are produced, this is mainly used by families as cooking fuel. Perhaps, however, the ash from cooking fuel could also be investigated for use as a pozzolanic stabilizer.

10. Gaps in Indian Practice and SWOT Analysis

10. Gaps in Indian Practice and SWOT Analysis

The Indian manual for low volume roads (IRC SP 72: 2015) is a significant improvement over the 2002 IRC SP 20 document, and contains many innovative and creative philosophies. Unfortunately, however, these are currently not implemented to the fullest extent possible. This may in some cases be due to a number of gaps in the document, but also to the conservative nature of many engineers who fear moving away from the norm.

The use of material strength testing in the unsoaked condition is permitted in IRC SP 72. After visiting numerous sites in a number of Indian states, implementation of this procedure has not been identified, even in relatively dry areas with good drainage. While it is acknowledged that the use of unsoaked strengths would not be appropriate in many parts of India (e.g. Bihar and Assam), this procedure could result in significant savings in pavement material quantities, for instance in large parts of Rajasthan and other areas (normally receiving less than about 600 or 700 mm of rain per annum), and where flooding is unlikely.

IRC SP 72 specifies almost entirely the use of densities related to the light compaction effort (Proctor), although heavy compaction effort (modified Proctor) testing is included in the Indian Standard Test methods. Hardly any country still uses light compaction to specify the density of structural layers in roads. As stated previously, compaction is the least costly way of improving material quality, and the use of higher compaction requirements alone could save significant volumes of material and provide better pavements.

The use of water-bound macadam in pavement has been abandoned almost universally, unless specific requirements for increasing the use of labor on projects are an important objective included in the overall road provision process. Water-bound macadam has a number of significant disadvantages, only offset by the use of increased labor. These include:

- The handling of at least two and usually 3 (in typical Indian usage) different materials on site.
- It is almost impossible to control the density of water-bound macadam. Existing test methods have been found to be almost completely ineffective.
- High degrees of compaction with penetration of the fines through the full depth (using copious water) are essential for an effective structural layer.
- It is not possible to make use of more cost-effective and appropriate "thin bituminous surfacings" over the water-bound macadam layer. This is due to the unevenness of the finished layer, as irregularities of more than 10 mm are inevitable with such a coarse upper layer. These irregularities affect the uniformity of the premix asphalt layer thickness, with many cases observed of very thin areas of asphalt over large particles.

- There is a wide range of prime application rates on the final surface due to ponding between large surface stones, and preferential absorption of the prime in the fine material compared with the aggregate.
- Once potholes develop in water-bound macadam, they enlarge rapidly due to the low cohesion of such materials. Potholes often develop within the first year as a result of the thin cover with premix asphalt, or even exposure of the large aggregate particles (many of which are loose and able to "rock") in the road surface.

IRC SP 72 permits (and in fact even encourages) the use of local and waste materials. Very few examples of such usage have been observed in India. Where waste materials have been used, insufficient controls have been taken to optimally monitor their cost-effectiveness and performance. Concerted effort is required to identify the properties and performance of the common by-product materials widely available. Much work has been done and can be found in the Indian literature, but little of this is taken to a successful conclusion that will allow the material to be confidently used in construction. The use of such materials often requires careful production and processing as well as modified construction processes. These are, however, not complex, and only require minor adjustments to normal construction processes.

India has an excellent three-tier quality assurance process developed for use on PMGSY projects. Observations in the field, however, indicate that it may not always be fully implemented. Many examples have been observed where simple problems, which should be picked up during the quality testing and inspections, are overlooked, resulting in premature problems.

The maintenance contracts implemented on PMGSY roads are laudable and extremely innovative. However, although regular inspections of any problem on the road are made, discussions with a number of maintenance contractors indicate that the problems appear to be attended to less frequently. This could result in a pothole or crack in the road being unattended for up to 6 months, during which significant deterioration and other problems could develop, leading to extensive areas requiring maintenance. Some basic maintenance principles are also overlooked in some cases. Issues such as the build-up of material on the shoulders, resulting in the shoulder sloping in towards the paved carriageway have been noted regularly on PMGSY roads.

Additional innovation and initiatives by local engineers should be encouraged. Many cases were observed where, for instance, a strong existing pavement was to be "deconstructed" before being upgraded. This was particularly the case with brick-soled roads, which had only localized problems. It would be far more beneficial to retain the existing structure, repair and widen the road where necessary, and then add perhaps one new layer and a bituminous seal.

The ubiquitous use of premixed asphalt (both hot and cold) on low volume roads is considered to be costly and often inappropriate.

The limited availability of good construction materials is a major challenge in a number of states in India. This results in the need to modify or strengthen local materials using mechanical or chemical stabilization. Observations and discussions with local engineers indicate a lack of fundamental understanding regarding most chemical stabilization procedures and requirements. The rule of thumb is to add a specified (not based on any scientific criteria) quantity of cement (typically) to a soil. Many instances have been seen where the addition of 3% cement results in an increase in CBR from 2 or 3% to a value of about 6 or 7%. By international standards, this would be considered a waste of cement (strengths of 750 to 1,000 kPa would be typically expected for a 3% cement treated material). A proper stabilization design, in which the optimum cement content (lime would probably be a better stabilizer for many of the Indian local materials – for instance the silty clays in Bihar) should be carried out. This would involve identifying the optimum stabilizer type and content based on a simple "initial consumption of stabilizer" study.

A summary of the gap analysis on Construction Materials and Specifications and the use of by-product materials is as follows:

- Little detailed information on use of "wastes" (better termed as "by-products")
- Nothing currently on mechanical stabilization/blending of by-products even though IRC:SP:72-2015 allows for this
- No detailed guidelines for using by-product materials
- Some pavement layer strength requirements unnecessarily conservative for very light traffic
- Exclusive use of water bound macadam (WBM) for base even though alternative material types now allowed in IRC:SP:72-2015
- Generally insufficient consideration for the use of locally available materials, even though IRC:SP:72-2015 now promotes this
- Insufficient information on stabilization design procedures
- Aggregate specifications not always appropriate for low volume roads, e.g. PSV of more than 55 required

A simple SWOT analysis has indicated the following issues related to low-volume road construction in India:

TABLE 2: SWOT ANALYSIS OF ISSUES RELATED TO LOW-VOLUME ROAD CONSTRUCTION IN INDIA

Strengths	Opportunities
• Competent engineers • Good manuals • Long-term commitment to PMGSY roads – contractors can thus justify obtaining new and modern equipment • Medium-term maintenance contracts • Effective accelerated testing facilities available in India • Need for innovative materials	• National policies (PMGSY) • Creation of new SMMEs and industries • NRRDA policies (15% innovation) • Upgradation of the construction industry • Job creation at low levels • Development of by-product "champions"/experts • Environmental and sustainability benefits
Weaknesses	**Threats**
• Lack of suitable materials • Old and inappropriate construction equipment • Lack of overloading control norms • Ineffective implementation of maintenance contracts • Apparent shortage of engineers knowledgeable in by-product materials	• Conservative engineers (fear of failure) • Ineffective quality assurance implementation • Depletion of good construction materials • Climate change • Monopolies take control of sources (increased prices) • Parts of some manuals and specifications outdated

In general, the strengths and opportunities far outweigh the weaknesses and threats, and the potential for the greater use and implementation of by-product materials in India looks very promising. It is for this reason that the recommendations in Chapter 12 of this report should be implemented as soon as possible.

11. Experimental Sections and Monitoring

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11.1 Experimental sections

It is important, if not essential, when assessing new technologies or innovations, that experimental sections are carefully designed and constructed. In order to ensure their cost-effectiveness and performance when compared with the conventional or standard processes, the experimental design must be such that the trial and the standard construction are directly comparable. This means that only one variable should be different in each trial section, and the two comparative sections must be constructed identically, with only the experimental requirements being different.

The site of the trial should be similar in terms of sub-grade, drainage and traffic. Construction processes on each layer must be identical (i.e. the same equipment, numbers of roller passes, etc.), with the only differences being in the treatment necessary for the trial section or product (i.e. mixing, curing, etc.). If any additional plant is required for construction (e.g. for mixing in a stabilizer), the costs of this must be included in all cost analyses.

On most experiments it is conventional practice to monitor aspects such as traffic volumes, types and loading. This could prove essential in analyzing cases of premature failure, which may be due to overloading or unusually high volumes of heavy traffic. Similarly, the weather conditions should also be monitored as close to the experimental sections as possible. This would usually primarily consist of rainfall measurements, but experiments using bituminous surfacings and even concrete could require temperature measurements as well. The combination of rainfall and heavy traffic often leads to premature distress.

A number of experiments have been seen where there have been more than one or two different treatments in a single trial section. In these cases, it is impossible to relate benefits or failures to any single difference in any of the sections. One section was even seen where the natural material was treated with a commercial product and the "control" section was a Portland Cement Concrete (PCC) road. No useful assessment of the possible benefits of the innovative treatment can be obtained from this type of experiment.

It is also often useful to design experimental sections to fail after a limited period (say 18 months or 2 years) in order to actually obtain data that can be related to the performance of the road. In these cases, it is essential that signboards are placed, indicating that the section of road is undergoing experimental observation, and actions to correct any problems quickly must be set in place.

11.2 Monitoring

The monitoring procedures and processes must be based on the objectives and aims of the treatment. This will vary from strengthening a poor material, stiffening a layer, waterproofing a material or substituting an expensive conventional material with a more cost-effective local material. Because of this, the monitoring programme for any trial section must be developed specifically for that trial and must include regular measurement of the important properties being investigated.

An example of poor monitoring in this respect is, for instance, in the case of waterproofing of materials (increasing their resistance to strength changes with moisture fluctuations), where only periodic DCP testing has been carried out as opposed to regular sampling and laboratory measurement of the actual *in situ* moisture contents. Although the DCP can indicate losses in strength due to moisture changes, other influences such as soil variability and density variations may be equally important in affecting the test results.

Monitoring requirements will thus depend strongly on the actual innovation being investigated, and the monitoring programme needs to be designed around this. It is also essential that any localized distress is repaired as soon as it is observed (keeping records of the type of repair and dates, as well as the cost of the repair, which will later be used in life-cycle cost analyses) to maintain the structural integrity of the pavement. Unmaintained cracks and potholes that may originate from a localized problem during construction (dry or wet patch not compacted fully, clayey materials, etc.) may allow water into the road, which results in extensive failures that would not have occurred had the road remained in good condition, biasing any final conclusions.

Where a layer has been constructed with some form of innovation that is required to increase its strength, monitoring should be such that this property is measured directly. Typically, DCP testing is the best way of assessing the *in situ* strength of such a material directly, but the seasonal changes in moisture content need to be taken into consideration. This requires comparison of the strength of the material at regular intervals in more than one location with the strength of the same untreated layer in the adjacent control section. The use of only peak deflection measurements, for instance, to do this, is not possible as changes in the strength of other layers will affect the peak deflection. It is not possible to attribute the changes directly to the experimental layer. Falling Weight Deflectometer (FWD) measurements can be used, but even these make the back-analysis of stiffness of the various layers difficult to compare, as the procedures are iterative, requiring a balancing of layer stiffness. In a case like this, both DCP and FWD measurements, together with moisture determinations, would be able to provide sufficient information to assess the impact of the treatment.

Monitoring should be carried out by specially appointed independent monitors with no personal connection (vested interests) with any of the products being tested. They should be experienced in the type of pavement being assessed and understand all of the fundamental principles related to the functioning of the specific type of pavement and the innovations being implemented, where necessary. For instance, a cement stabilized layer would need to be assessed totally differently from a relatively strong granular material or a sub-grade that has been improved using a proprietary chemical. Retired state engineers, experienced academics, research scientists and engineers and consultants with special knowledge of certain pavement areas should be contracted to monitor experiments.

Experiments should be monitored on a semi-continuous basis, and certainly assessed immediately before any maintenance or repair intervention is carried out, and at least before each change in precipitation season. Visual assessment according to a nationally accepted scheme (to remove subjectivity) should be used during all assessments, and appropriate non-destructive testing carried out. This could include FWD, Benkelman Beam, Lightweight Deflectometer (LWD), DCP, and associated testing of moisture content and material sampling, where necessary. Care needs to be taken when using nuclear measurements for moisture, as there can be large discrepancies in results, and all nuclear density readings should be corrected for the actual gravimetric moisture content. Wet density determinations are normally correct, but the use of incorrect moisture values results in incorrect dry density and relative compaction values.

11.3 Monitoring period

It is important that monitoring of the trials is extended over an adequate length of time to be able to include maintenance interventions in the overall costs. ***The only way to compare different options is by using the overall life-cycle cost analyses (LCCA) of each, which must include the costs of maintenance and the salvage value as well, where possible.*** A minimum of one life-cycle of the conventional pavement should be allowed in such experiments.

Because of discounting in LCCAs, and depending on the discount rate used, the costs of interventions after about 7 or 8 years have a minimal impact on the total life-cycle costs. Monitoring for a period of five or six years will therefore normally allow a reasonable LCCA to be carried out. Attempts to quantify and include any environmental benefits in the LCCA should also be made.

A properly planned and executed monitoring programme is essential to get any useful information from experimental sections. Senior staff at CRRI or other research institutes should be consulted to assess and advise on proposed experimental designs and monitoring programmes, in order to obtain the maximum benefit for what are often costly and time-consuming exercises.

12. Implementation

12. Implementation

The implementation of new and innovative technologies is always difficult to initiate. New technologies bring the fear of premature failures and/or claims to many consulting engineers, who can design roads based on standard procedures ("recipe designs") with no fear of any problems occurring. If failures do occur, they are normally attributed to poor construction, excessive overloading or extraordinary climatic conditions. ***An enabling environment to assist with implementation thus needs to be created.***

12.1 The status quo

As discussed in the preceding text, significant research has been carried out over the past few decades on the use of alternative materials. This has been published in local journals and at local conferences mainly. A workshop organized by NRRDA with about 12 very informative and useful papers was held in 2012 in Delhi[3], but little knowledge of this event and the papers was noted during visits to various states. Many of the papers contained rich theoretical discussions, laboratory and field-testing results, but few actually provided sufficient information on wider field application.

Despite all of this work, there is still some trepidation in using such materials. ***This highlights the importance of having knowledgeable "champions" in each of the states (see below) promoting the use of these local materials.***

12.2 Early implementation

The "**low-hanging fruit**": A number of technologies described in this document have been developed to a significant degree internationally, and can be implemented with little additional research or development in India. These include such technologies as:

- The use of slag materials
- Chemical stabilization
- Mechanical stabilization
- "Recycling" of mine wastes
- The use of products such as fly ash, phosphogypsum, granulated blast-furnace slag, etc.
- The use of recycled asphalt (RA)

3 Workshop on Non-Conventional Materials/Technologies, 18 February, 2012, Central Road Research Institute, New Delhi.

Significant international research has been carried out on these techniques and products, and their use in road construction has been "tried and tested" in many countries. Additional research in India is probably unnecessary. Only the implementation of international experience, initially in the form of demonstration sections, needs to be carried out in order to confirm that such experience is applicable, valid and cost-effective under Indian conditions.

Such implementation should follow international best practice, with appropriate testing, monitoring and evaluation. It is important, however, that similar test methods and construction procedures to those used internationally are followed to ensure that the fundamental principles are retained.

Other less-established technologies using unusual by-product materials will need to follow the traditional research process as illustrated below:

TABLE 3: TRADITIONAL RESEARCH PROCESS FOR LESS-ESTABLISHED TECHNOLOGIES

Stage	Objective	Details
1	Desk study	To assess and evaluate existing information on the material
2	Laboratory study	Tests of the mechanical properties of materials to allow theoretical predictions of performance
3	Pilot-scale trials	To evaluate construction and performance of materials in small scale trials
4	Full-scale trials	Trial to establish whether the previous assessments obtained from Stages 2 and 3 are realized
5	Road Authority specification trials	This stage is necessary to carry out further evaluation of the material and to test the specifications under contract conditions

12.3 Creating an enabling environment

An appropriate institutional and support environment is essential to promote and establish new/innovative technologies.

It is already required that 15% of the length of all NRRDA roads shall include some innovative technology. However, field observations indicate that many of these initiatives make use of "safe" technologies that are unlikely to result in any visible problems if they are not successful, e.g. the use of recycled plastic bags in asphalt. In many other cases, more than one technology has been included in the same "experimental section", which results in difficulties in attributing changes in performance to any one cause.

Government initiatives such as these are almost essential in ensuring the uptake of new technologies. This is particularly the case with the use of alternative/by-product materials, where economic opportunities need to be instituted early in the production stream. This may range from initial sorting and processing of the products to the provision of incentives to small entrepreneurs to actually collect, process, stockpile and deliver such materials.

It is important, however, that once a material reaches such a stage, its value does not become artificially distorted so as to make it uneconomic for use in low volume roads in rural areas as compared to traditional materials.

At the same time, it is essential that a number of "champions" of the by-product industry are identified and nurtured. These must be open-minded engineers or material specialists, who have both a deep understanding of the behavior and properties of road construction materials, as well as conviction regarding the beneficial attributes and advantages of increasing the use of non-traditional materials in road construction. Initially, engineers already involved in investigations of such materials should be identified and developed as "champions" in this field of construction materials. These champions should be identified from State road authorities, universities, by-product producers and research organizations, and trained as a group to develop the innovative road construction materials field. This will be through attendance of international courses and conferences, and increased liaison with international by-product experts and bodies. It is recommended that at least one champion be developed in each state.

Creating champions will involve the dedicated participation of a number of bodies, including National and State road authorities, universities, CRRI and product manufacturers/marketers. This participation will not only include the allocation of time and resources to the initiative, but also potential collaborative funding in order to properly initiate and then accelerate the process. Funding should be allocated from all of the parties involved, particularly the suppliers who are likely to gain the most. This is because suppliers will ultimately gain by having commercial products that can be marketed, hopefully at competitive prices by the suppliers, with appropriate technical support. ***It will be important to involve National road authorities, as many of the potential products that will be assessed will be suitable for roads of the highest standard as well.***

It is anticipated that fundamental background and knowledge will be gathered by the universities, probably with support from professional researchers such as CRRI and other research institutes, while the field experimental work will be coordinated by the State road authorities. A team of high profile experts (national and international) should also be assembled to assist and guide the local researchers, and provide critical reviews of the outputs as they are produced.

The main objective of all of the research and development will be to produce comprehensive guidelines, user manuals and specifications for each of the viable by-product materials. This will then need to be adopted and promoted by the Indian Roads Congress as official documents. Once this is in place, it is the responsibility of the client bodies to ensure that local non-traditional materials are at least assessed as alternatives for every proposed project. If these are found to be economically attractive options, they should be included in the tender documentation.

In order to increase the competitiveness of such interventions, it will also be important to develop a programme of research that will determine financial values for issues such as the use of non-renewable natural resources (e.g. a realistic, aggregate tax), environmental benefits (e.g. release of land, reduced pollution) and other sustainability issues. These values should be included in any economic analyses.

Studies of overall costs/benefits of each potential product should be initiated in order to justify their introduction, and convince otherwise skeptical practitioners of the potential benefits. This will require individual investigations of each material, and assessment of the local cost and competitive product conditions.

Tools for analyzing costs and benefits exist (e.g. the World Bank RED and HDM 4 software packages) but actual local processing, transportation and handling costs of alternative materials in comparison with the conventional materials need to be determined. In such cost/benefit analysis, it is important that environmental and sustainability benefits (and costs where they occur) are incorporated. It is, however, difficult to attribute actual costs to such issues in general, although the release of land, savings in aggregate tax, etc., can usually be quantified.

During development of the inventory of potential material resources as discussed in Sections 5 and 12.6, it will be useful to identify the "zone of economic use" of each material. The materials may each have a unique basic production cost (perhaps a nominal purchase cost as well as some processing costs such as crushing, screening or sorting). The zone of economic use for each resource will depend on the typical transportation costs in the area as well as the cost of the materials normally used. A series of concentric circles around the source can then be constructed, with the higher quality materials (e.g. base and surfacing aggregate) normally having the largest radius and lower quality materials (sub-base and selected fill) having smaller radii of economic use.

This type of analysis is more appropriate than having a single chart, for example for haulage distance versus cost/km, due to large variations in transportation and basic material costs in different regions.

12.4 The complete road package

The use of innovative materials, the "environmentally optimized design" method and application of alternative surfacings in low volume (PMGSY) roads must be viewed as a complete package included in an overarching road delivery process. Each of the inputs must be compatible with the others, and all are subject to certain overall requirements and fundamental responses.

For instance, the use of the EOD method assumes that the design assumptions are maintained throughout the life of the road. These include issues such as minimal overloading of vehicles, well designed and maintained drainage systems, properly controlled construction quality, and regular, high-quality road surface and shoulder maintenance. Should any of these not be properly fulfilled, the risk of premature failure of the pavement structure increases significantly, particularly as many of the innovative pavement materials may be moisture-sensitive and operating close to their tolerable mechanical and physical limits.

For optimum use of local or alternative materials, a specific strategy should be followed. This will include:

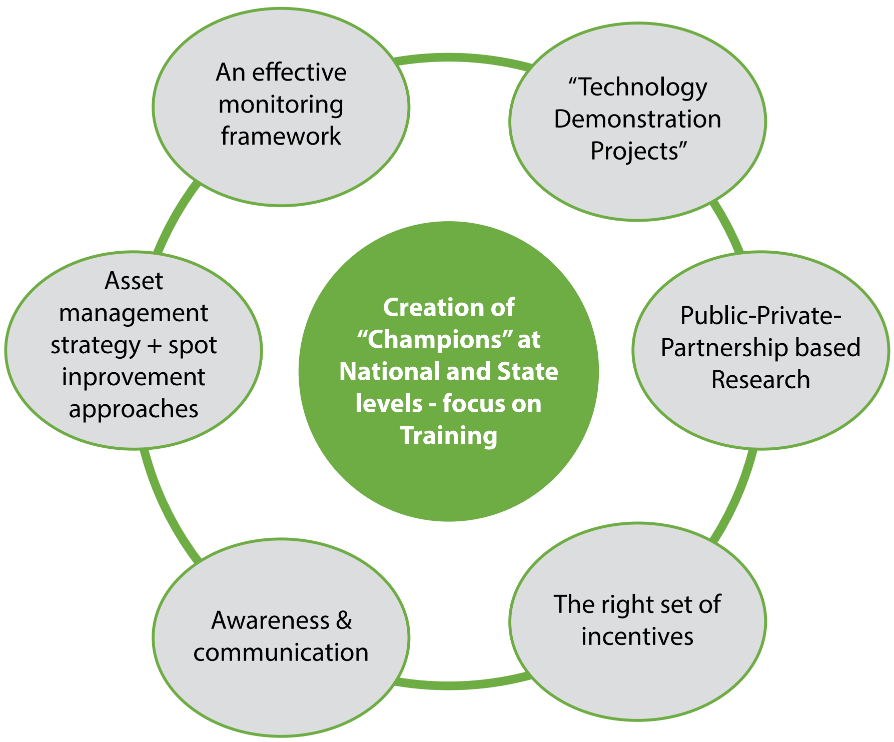
1. An assessment of the local sub-grade conditions, typically done using a DCP in order to allow as many tests as possible along the road alignment.
2. At the same time, representative samples of the *in situ* and local materials available for possible use in the pavement should be carried out. All potential by-product materials in the vicinity of the road should be identified and representative samples collected.
3. The road sub-grade should be divided into uniform sections on the basis of the DCP survey, and for each sub-grade section, the design requirements should be determined using the EOD design method.
4. Where the sub-grade strength is inadequate, methods for improving it, whether through mechanical or chemical treatment, should be investigated. This would normally initially entail laboratory investigations of different blends and types of local natural and by-product materials, in order to attempt to increase the material strength as much as possible, while remaining economical.
5. Only if mechanical improvement is ineffective in achieving the required material strength or becomes excessively difficult, should chemical treatment be considered. In this case the optimum stabilizer content to achieve the necessary strength must be determined in the laboratory.
6. The process can then be repeated for possible materials for use in the structural layers, initially using mechanical improvement before chemical improvement, to arrive at the most cost-effective materials design.
7. If the required strengths cannot be achieved, then alternative materials imported from farther away would become necessary in the pavement structure.

The importance of good and regular maintenance cannot be overemphasized. Where unsoaked pavement designs are employed (the basis of much of the EOD method), it is essential that precipitation is removed from the road environment as quickly and effectively as possible. This requires well-designed drainage (side and cross drains) that are kept clean and effective in addition to being well-shaped and well-maintained shoulders that facilitate the rapid and total removal of precipitation from the road surface to the drainage systems. This requires regular de-silting, grass and bush removal and reshaping where necessary.

12.5 Incentive structure and institutional issues

There are numerous approaches that could be taken to encourage risk-taking in the use of alternative materials, and each specific environment calls for a slightly different approach. It would be virtually impossible to write standards and specifications to address all the options identified in this report. As the report highlights, it will ultimately depend on the judgment of individual engineers within the framework of more flexible standards and specifications. However, the key will be empowering engineers to take these risks, to think about each situation separately and create an environment where innovation is rewarded. ***This will require a new approach to the training of engineers which should be central to the strategy.*** This is explained below:

Figure 8: An incentive and institutional structure for adoption of sustainable materials/technology



1. The current institutional organization for roads in India is generally adequate for the implementation of the increased use of local and by-product materials in low volume rural roads, and no major structural changes (e.g. establishment of a Road Agency or dedicated Road Fund) are considered necessary. ***There is, at the same time, a need for creating "champions" both at NRRDA as well as the state level.*** These champions will need to be knowledgeable and believe fully in the benefits and potential of alternative materials, both in the interests of economy and sustainability. Such champions should be identified from within the existing staffing structures and singled out for **specific and sustained training** (technical training, as well as training to address resistance to change within their organizations) and instruction in the location, sampling, testing, use and monitoring of such materials and their performance. Champions need to be identified carefully and should have a good fundamental understanding of material properties, rock and soil chemistry and mineralogy, structural behaviour of roads and materials, long-term effects (durability) of these materials and the desire to see constructive and innovative change.
2. ***With the "champions" in place, the next step would be to undertake "Technology Demonstration Projects" on the use of sustainable materials/technology.*** These projects would involve co-opting field engineers right from the research planning phase, documenting all key technical and implementation

processes, and disseminating these to more field engineers through regional workshops and other events. This would, in turn, increase their exposure and instill confidence in them for large scale adoption of these alternative materials/technologies. The successful demonstration of these projects would also showcase the cost effectiveness, potential for "green jobs" as well as conservation of natural resources and climate change impacts of these initiatives, in the long run. It would address the issues of lack of awareness, and inability to instill confidence in field engineers because of their problems going unaddressed, which have held back the use of new materials and technologies in India.[4]

3. ***It is also important that the research backbone for the use of sustainable materials be strengthened.*** Each of the materials identified has unique properties, which need to be investigated and researched, in order to benefit optimally from their uses. Many of the by-product materials can be used in combination with local materials (e.g. fly ash and slag). In these cases, specific investigations need to be carried out with the various combinations because of the variability in the properties of the local natural materials. This is, however, the type of research that can easily be carried out by researchers at universities and research institutions as part of post graduate qualifications (Masters and Doctorate degrees). Another form of research that could possibly be replicated in India is **public-private partnership-based research** which has been used successfully in the transportation sector in Korea. This involves research and academic institutes playing a key role in mainstreaming the use of alternative materials and technologies by inviting interested private sector agencies to be partners in their research programs, and then using a combination of their own and private sector funding to conduct the core research. Once the core idea matures, the private sector partner applies for patents and subsequent commercial application. The research institutes get a predetermined share (about 3-5%) of the revenue (profits) from commercial application.

4. ***In many cases incentives are required to initiate the implementation of new and innovative ideas.*** The "compulsory" inclusion of 15% of all new PMGSY construction being devoted to innovative materials and methods is certainly a good incentive for most engineers, as the risk of premature failure of the roads is mostly removed from their responsibility. However, incentives are best done on a more personal scale with the implementation of recognition criteria (prizes/awards) for individual staff members or teams who successfully implement innovative ideas or solutions, that will ultimately lead to wider understanding and adoption of such materials/technologies. It has been found that nominal monetary awards are the most effective technique for this.

5. ***In order to implement new innovations, it is also essential that they are widely communicated to potential users.*** It is also essential that their benefits are clearly represented, and that potential users recognize and accept that there are these benefits, either observable (lower cost and/or better performance) or intangible (more sustainable). This requires wide publication of success stories, frequent feedback at seminars and workshops and hands-on sessions with engineers. It is also important that the public is made fully aware of the presence of experimental and research work on roads, in order to justify any problems that may occur. It should be borne in mind during such trials that far more is learned from things that go wrong, than from experiments that perform extremely well. In the latter, the road is probably over-designed but it is difficult to determine by how much, while premature failure identifies the shortcomings more easily.

6. ***Key to the success of any approach, but particularly one using marginal materials, is effective maintenance.*** An **asset management strategy** particularly focused on the use of marginal materials and innovative technology would thus need to be expressly developed. Linked to asset management is also the issue of using effective **spot improvement approaches** where particularly vulnerable parts of the network may be improved to a higher standard for climate resiliency.

4 Adopted from "A critical review of rural road construction techniques and their impacts, M. Vedula, Pawan Nath G., Prof. B.P. Chandrashekhar, National Rural Roads Development Agency".

7. ***Finally, continuous monitoring of acceptance, adoption, refinement and results of use of alternative materials through an effective monitoring framework*** would be key to keeping up the momentum and scale of efforts.

The use of an environmentally optimized design in Vietnam, including spot improvements for protecting key sections of road links from floods or other climatic impacts, is presented in Box 1.

Other suggestions on improving the current institutional framework for use of alternative materials in India include:

1. While the current Detailed Project Report (DPR) process provides a comprehensive, traceable and complete design procedure for each project, making budgeting and implementation consistent, DPR requirements can sometimes be quite restrictive, and innovation can be limited. It is suggested that more **flexibility in the production of the designs and the DPRs** should be permitted and in fact encouraged.

BOX 1: USE OF ENVIRONMENTALLY OPTIMIZED DESIGN IN VIETNAM

In Vietnam, as in most rapidly developing countries, an effective Rural Transport Infrastructure (RTI) plays a crucial role in rural socio-economic progress and in reducing poverty. A basic ingredient of this is a road network that can be maintained in a condition that facilitates all-year, all-weather access for transport services. Rural roads are a lifeline for rural communities and in consequence the Vietnamese Government, with the support of international development organizations, has made a focused effort to invest in rural transport.

Inclusive rural development requires assets that meet the measured needs of the community. Sustainability requires that the assets are designed, constructed and managed to meet their purpose, or task, and that they are compatible with the local road environment. Climatic risk has major potential impacts on economic development, and decision-makers need to have the tools to integrate climate adaptation with economic development, rather than tackling climate risk as a stand-alone issue. Thus, the key question is not "How can we minimize the damage from climate hazards?" but rather "How can we reach our development targets while accounting for current and future risks?"

In recent years there has been a growing perception that existing Vietnamese standards and specifications for Low Volume Rural Roads (LVRRs) are often mis-matched both to the tasks these roads may be required to perform and to the natural environment factors influencing their performance; including the impact of terrain, rainfall and flood. Many of the problems of sustainability in RTI can be linked back to issues of inappropriate standards, specifications and consequent unsuitable design and poor construction control. Increasing climatic impact will further expose the marginal sustainability of much of Vietnam's LVRR network.

Appropriate design is key to producing a sustainable RTI asset within affordable budgets, and the use of an Environmentally Optimized Design (EOD) approach is increasingly seen as an attractive solution. EOD in general terms seeks to link the key elements of the road environment and its identified tasks, into a flexible design. LVRRs can then be constructed with varying geometric and pavement/surfacing designs according to the road environment needs. In budget constrained situations the Spot Improvement element of the EOD approach offers a way in which scarce resources can be effectively concentrated on the most vulnerable sections (or Spots) along a rural road or track. Spot Improvements may vary from the provision of cross drainage to the construction of short concrete sections on vulnerable sections of an otherwise unsealed road link. *This EOD Spot Improvement approach may be ideally suited to protecting key sections of a road link from floods or other climatic impact.*

The Rural Road Surfacing Research Program has resulted in the systematic acquisition of 5 years of knowledge on the performance of a wide variety of pavement and surfacing types, including the impacts of recent severe storm events on a variety of pavement types. This enables meaningful analysis to be undertaken in terms of deterioration patterns related to pavement design and the natural environment. This work clearly demonstrated that there are more robust and resilient feasible paving options potentially available for use in Vietnam using designs within acceptable Whole Life Cost constraints.

Source: World Bank

2. Construction would be greatly improved if **contractors** were appointed more on their past records, the quality of their staff and equipment, as well as their perceived potential to provide a good end-product. Registration/pre-qualification of contractors may assist in this regard, and help avoid instances of premature failures of roads.

3. The existing **three-tier quality control system** is comprehensive and in most cases, all-embracing, but would lead to much longer service lives of the PMGSY roads if it were more effectively instituted. During the many site visits carried out, deficiencies in implementation were frequently observed.

4. The **5-year maintenance requirements** on new PMGSY roads, too, are laudable and should yield valuable returns. However, these need to be properly and effectively managed to ensure that maintenance is carried out regularly. This would require more input (and probably training) from local road inspectors/supervisors, whose numbers may need to be increased.

5. Large benefits could also be achieved by **increasing cooperation between different agencies** in India. Probably the most important of these would be with the police, to ensure effective overloading control and prosecution of offenders. This would result in substantial increases in the lives of many of the roads. The income from penalties/fines could be invested back into the management and maintenance of the roads. Similarly, by utilizing existing structures falling under the jurisdiction of other departments such as "Irrigation and flood control", such existing embankments would provide good structures for placing of roads with significant sustainability benefits, by reducing the need for large quantities of new materials.

6. ***The use of by-products and local materials is not restricted to low volume roads and, in fact, materials such as slags, fly ash and construction waste can be used for many roads not classified as low volume.*** Existing national and rural road specifications allow for the use of certain alternative materials, and their use should be encouraged in the overall road development industry. Some areas of minor improvement in the **existing documentation, design manuals and specifications** would result in significantly improved roads with minimal additional cost (e.g. compaction to higher densities). However, in the context of this report, the main area of interest is low volume rural roads.

It should be borne in mind that alternative materials will mostly be used as replacements for aggregate in pavement layers, as blending/stabilization materials (both mechanical and chemical) for weak sub-grades and sub-bases, and for their bulk use in fills and embankments. Many of the road solutions currently suggested as "innovations" (e.g. chemical stabilization, use of slags and local gravels, etc.) are really novel only in India and have been implemented with success internationally for decades. This vast international experience should be collected, collated and considered and then adapted (in appropriate manuals after the necessary local research) for implementation in India. ***Other innovations, such as the use of waste plastic in asphalt, are unique to India and deserve more investigation and development.***

Many of the suggested improvements in institutional arrangements can be related back to one common denominator – institutional capacity building (ICB), whether it be training, improvement of systems, better implementation of existing or improved methods, or purely improved supervision and management. ***Sustained training to field engineers and the development of a "risk-taking culture" is, however, the keystone of this strategy.***

It appears clear from the observation of local practice and discussion with stakeholders in India, that the intangible capacity is mostly in order but the tangible, day-to-day institutional arrangements and capacity could be incrementally improved.

12.6 The way forward

The proposed way forward is as follows:

1. Develop an **inventory** of ***all*** possible by-product materials (including those that are currently considered highly unlikely to ever be used in roads). Some states appear to have initiated this to some extent.
2. Identify appropriate and willing potential **champions** for by-products in the academic, research and state bodies, and establish an informal working group. This would need to be approved and supported by the supervisory bodies involved (universities, road authorities, research organizations, product suppliers, etc.), and should identify potential sources of funding, which can then be motivated.
3. Identify those **materials** from the inventories that have been developed, which occur in significant quantities, currently have disposal problems or high storage costs, and, based on existing knowledge (international or local experience), have the potential to be used in road construction.
4. Initiate **research and development** on these materials to fill in existing gaps in knowledge regarding their properties and use. This would mostly be literature and laboratory based and would be coordinated by the local champion(s).
5. Support the fundamental research using full-scale trial sections and accelerated testing where feasible.
6. Develop specifications, new test methods where appropriate, user guidelines and manuals and disseminate the findings widely.

13. Conclusions

13. Conclusions

This report discusses the use of materials for the construction of low volume roads, with a strong emphasis on "green" issues and sustainability. The status quo in road construction using natural materials cannot continue sustainably as good materials are consumed. Further, assuming that road provision does not change dramatically, future generations will not have suitable materials for road construction.

There are many potential by-product materials in India that could effectively and economically be used as road construction materials, up to base course level for low volume roads. International experience can be used to guide the specification and use of many of these, while local research and development may need to be carried out on others. The environmental benefits of using many of these materials cannot be underestimated.

However, new and innovative materials need to be "tested" in properly controlled full-scale experiments on normally trafficked roads with the appropriate monitoring and analysis for the material being investigated. A summary of by-product materials and their potential advantages and disadvantages for use has already been presented in Chapter 5.

There are also many ways of improving unsuitable materials to the point that they may be used in structural layers in roads. This could include mechanical, chemical or bitumen stabilization, all of which can be easily carried out on most projects.

For any innovative material, it is essential that the life cycle benefits are determined using full life cycle cost analysis procedures, to ensure that their use is cost-effective. Issues such as environmental benefits should be included in the analyses, although these are often difficult to quantify.

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