USE OF TYRE RUBBER IN BITUMINOUS PAVEMENTS IN NEW ZEALAND

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AN IMPORTANT NOTE FOR THE READER

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EXECUTIVE SUMMARY

Natural rubber and, more recently, synthetic rubbers have a long history of use in New Zealand road surfacing construction. Since the 1970s, the use of tyre rubber (ground to crumb-sized particles, to produce ground tyre rubber (GTR), also called crumb rubber) has become an alternative additive to bituminous binders for pavement construction internationally.

A literature review was carried out in 1993 that concentrated on the potential use of crumb-sized GTR, obtained from recycling waste tyres, as an additive to the bitumen used in constructing New Zealand pavements. About 1.3 million waste tyres per year were generated at that time by the motor industry in New Zealand. Most of these tyres are being disposed of in landfills, where they can create difficulties in compaction and can tend to "float" to the landfill surface. Recycling waste tyres as GTR for use in road pavements has potential for the disposal of some of these tyres.

The review found that, in 1993, two main processes were used to incorporate GTR into bituminous surfacings:

1. Wet process - where GTR is blended with hot bitumen and applied as a sealing binder or used in a hot asphalt mix;

2. Dry process - where GTR is added to the aggregate in the production of hot asphalt mixes.

The conclusion was that:

1. The wet process used currently is not expected to be cost competitive with the block copolymer rubber (SBS or styrene-butadiene styrene) binders used in 1993 because of the following factors:

   (a) Specialised mixing plant is required near the construction site as the blended bitumen-rubber binder has a limited storage life.

   (b) Specialised distributors, that can cope with both the high viscosity and the rapid segregation of the bitumen and GTR, are required to spray the blended binder.

   (c) Cost of GTR is expected to be at least NZ$1,000/tonne (as at 1993) as cost includes controlling the proportion of truck to car tyres (which differ in their natural rubber content), as well as grinding and sieving the tyres to a relatively narrow size grade range (of 3-6 mm diam.).

   (d) 20-25% (five times more) of GTR is required to produce a binder with performance properties similar to those obtained by a binder containing only 4-5% of SBS.

2. GTR has a potential use in asphalt mixes produced by the dry process, only if the GTR can be easily included as part of the aggregate feed system in a drum mixing plant.

3. If GTR is used in asphalt mixes, using concentrations and aggregate gradings similar to those used in other countries, the cost of the mix could be expected to increase by approximately 50%.

4. The higher cost of GTR mixes would tend to restrict use of these mixes only to special situations where the enhanced performance would result in lower discounted costs than alternatives such as reconstruction.

5. In maintenance treatments, such as crack and joint filling or around maintenance hole covers, pre-blended bitumen-GTR appears to be cost competitive with other bitumen-rubber blends.

Insufficient information was available from the review to be confident of the cost effectiveness of mixes incorporating GTR. Trials would also need to be performed in order to determine the benefits under typical New Zealand pavement construction conditions.

ABSTRACT

A literature review was carried out in 1993 on the potential use of crumb-sized ground tyre rubber (GTR), obtained from recycling waste tyres, as an additive to bitumen used in constructing New Zealand pavements.

GTR, also called crumb rubber, has been used either mixed with bitumen or incorporated as part of the aggregate fraction in hot asphalt mixes.

The expected cost of the GTR and the cost of specialised blending and spraying equipment would make bitumen-rubber blends more expensive to use as a chipseal binder than the synthetic rubber being used in 1993 in New Zealand pavements. GTR could possibly be used in hot asphalt mixes where it would be expected to increase pavement flexibility at low temperatures.

Insufficient information was available to make a benefit/cost analysis of its use under typical New Zealand pavement construction conditions.

1. INTRODUCTION

Although rubber in the form of natural rubber latex or styrene-butadiene styrene block copolymer (SBS) has been used in New Zealand pavements since the 1970s, recycled rubber from waste tyres has not been used in normal road pavement maintenance or construction. For this use the waste tyres are ground to produce ground tyre rubber (GTR), also called crumb rubber.

This research project, carried out in 1993, aimed to:

- identify, in the New Zealand context, the potential and feasibility for recycling ground waste tyres in road pavements, taking into account the volume of waste tyres to be disposed of, roading practice, and experience in other countries;

- assess the magnitude of the volumes, and trends in generation, of waste tyres in New Zealand;

- carry out a literature search on the application of waste tyre rubber in road pavements;

- make recommendations for use of recycled waste tyre rubber in road pavements in New Zealand and the expected benefit/cost ratios.

2. BACKGROUND

2.1 Early Trials with Rubber in Pavements

The use of natural rubber in road pavement construction goes back to the 19th century. Despite generally favourable test results in countries such as Great Britain, France and Holland, a lack of raw material combined with technical difficulties and high cost prevented the extension of the tests to large scale applications before the 1970s.

Trials using granular natural rubber or ground tyres were performed in the 1930s but were discontinued during the Second World War. Trial sections in Great Britain, Holland and Indonesia showed good performance for periods as long as 22 years (DSIR (UK) 1962).

Initial attempts in the 1950s to use powdered tyre rubber were unsuccessful because of problems with blending the more viscous bitumen-rubber material, degradation of the bitumen-rubber when it is stored at high temperatures, and the high cost of the process (Marini 1971). Field testing by the DSIR (UK) Road Research Laboratory during the 1950s (reported by DSIR (UK) in 1962) produced some favourable results, particularly in crack sealing, but also produced some unfavourable pavements that failed soon after construction.

The availability of synthetic rubbers from the petrochemical industry in the 1960s offered reduced costs and more predictable properties of the bitumen-rubber blend. As a result much work since that time focused on the application of synthetic rubbers in pavement design.

2.2 Arizona Trials with Rubber in Pavements

In the 1960s development of bitumen-rubber progressed under the direction of Charles H McDonald, in Phoenix, Arizona, USA, as an option for reducing the incidence and severity of fatigue cracking of asphalt pavements. The major innovation made by McDonald was the use of recycled rubber in concentrations of 20-30% by weight of bitumen compared with earlier trials using concentrations of up to only 5% recycled rubber.

Large scale applications of a rubber-modified bitumen binder containing GTR were not carried out until 1966/67 when trials were conducted to repair severely fatigue cracked areas of the Phoenix Sky Harbour International Airport (McDonald 1971). The success in preventing reflective cracking on the airport runway led to continued research and field trials using GTR. It led to the placement of over 90 km of bitumen-rubber in Arizona during the period 1971-1979.

Research at this time by the Arizona Department of Transportation (Green et al. 1977) showed, among other things, that the elastic modulus of the bitumen-rubber is lower than that of conventional asphalt below 10°C and higher than that of conventional asphalt above 10°C. This difference in properties enables the bitumen-rubber to behave elastically and viscously over a wider range of temperatures than straight bitumen.

This initial work in Arizona used the bitumen-rubber blends as a seal coat in which the binder was applied hot and covered with an aggregate. Subsequent to this work the binder has been used in hot mixes where it is blended with hot aggregate in a central mixing plant and then laid with a paving machine.

Initially the relatively high costs of using bitumen-rubber blends in seal coats meant that only holding treatments could be funded. Some of these sections of highway which had previously required almost daily maintenance were still performing satisfactorily more than 10 years after the application of the bitumen-rubber seal coat (Schnormeier 1980).

2.3 Other Trials with Rubber in Pavements

Subsequent to the Arizona experience, other highway agencies in USA, Canada, and Australia developed bitumen-rubber research projects. Their research objectives were to identify the best techniques for blending GTR and bitumen, to investigate problems with placement of the material, and to assess the performance of mix designs with respect to crack propagation, friction, densification, ravelling, aggregate loss, oxidation/age hardening, etc.

The results of many other research projects and trials have been reported in the international literature including La Grone (1971), Schnormeier (1980), Esch (1982), Oliver (1984), Doty (1988) and Charania et al. (1991a, b). In particular, the results of recent investigations carried out by the Florida Department of Transportation in conjunction with the National Centre for Asphalt Technology have been reported by Ruth (1992).

3. WASTE TYRE DISPOSAL

3.1 Waste Tyre Disposal in USA, Europe and Australia

Research has been motivated by the increasing awareness that used waste tyres present a significant solid waste disposal problem. For example, in 1971 in the US alone, approximately 200 million waste tyres were produced in addition to 1 billion tyres already stockpiled at that time (La Grone 1971). In 1990 the number of tyres discarded had grown to 240-250 million tyres with a nationwide stockpile in the US estimated at between 2 and 3 billion (Logsdon 1990, Flynn 1992a, b). Other estimates of the number of tyres discarded per year are slightly higher at 280 million or approximately one per person (National Geographic 1992).

The US Federal Government passed the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991 which requires that, for a state to receive federal highway funds, asphalt containing recycled rubber must be above a minimum percentage of the total asphalt laid each year. The requirement was for a minimum of 5% in 1994 growing by 5% each year to 20% of the total asphalt laid in 1997. In addition, the legislation requires the Secretary of Transport to investigate the economic, technical, health and environmental impacts of using recycled materials in asphalt pavement (Flynn 1992a, b). Since 1991 annual growth in the use of GTR in asphalt pavements in the US is estimated at 35% (Prendergast 1991).

The Economic Commission for Europe (ECE 1985) has addressed the issue of dealing with waste tyres through a working group comprising 50 tyre makers, merchants, users, customers, retreaders, recyclers and ECE representatives. The "Used Tyre Project" has found that retreading is the most economic re-use of tyres, with European Community countries disposing of an average 23% of tyres in this manner. Landfill disposal accounts for 40-50% of used tyres, though the ECE report suggested that this should cease by the year 2000 (Bebbington 1991).

The State Government of South Australia is assisting Pacific Dunlop (an Australasian tyre manufacturer) to set up a fully integrated tyre recycling system that will collect used tyres, retread where possible, or otherwise shred and crumb the tyres using ambient and cryogenic (low temperature) grinding methods. Excess shredded rubber may be landfilled if required, with a volume saving of 75% on the 1 million cubic metres of landfill presently occupied by used tyres each year.

Over 3 million of the 10.5 million waste tyres discarded in Australia each year are intended to be recycled (Bebbington 1991). Other estimates of waste tyres for Australia place the number at 15-17 million per year, or approximately one per person, which is similar to the number in the US (Nixon 1992).

3.2 Waste Tyre Disposal in New Zealand

The generation of waste tyres in New Zealand currently stands at about 1.3 million tyres per year. The number of waste tyres in New Zealand grew by 32% over the three years 1988-1991, partly as a result of increasing imports of secondhand tyres. In the same period a reduction in the percentage of tyres retreaded has been from 50% to 35% of the total tyres sold (Consumer 1991), although retreading is reported to be the most efficient use of waste tyres.

The total of 1.3 million waste tyres produced annually in New Zealand compares with the waste tyre processing capacity of approximately 550,000 tyres per year planned for a facility in Perth, Australia, and with typical processing capacities of around 2.5 million tyres per year for large processors in Portland, Oregon, and in Sacramento, California (Nixon 1992, Grady 1987). However, the viability of waste tyre processing in New Zealand would be affected by transportation costs, which have also been of concern to operators in the US (Grady 1987).

Used tyres in New Zealand that are not retreaded are commonly disposed of in landfills. Difficulties with compaction of fill, and the tendency of tyres to "float" to the landfill surface, creating problems with landfill sealing membranes, have resulted in this disposal practice being banned in some US states as long ago as 1985.

The action of banning tyres in landfills in the US has meant that waste tyres are now stockpiled. Such stockpiles of up to several million tyres create other problems, such as those associated with fire risk and the spread of vermin. For example, research shows that breeding rates of mosquitoes in tyre piles is roughly 4000 times greater than in forest areas, and the northward spread of certain species of mosquito is of growing concern to local authorities in the US (Grady 1987).

In New Zealand the Ministry for the Environment has already indicated that restrictions on the landfill disposal of tyres could be introduced. From international experience, such restrictions might also require that storage sites for tyres will have to be registered or monitored in some way, that a "disposal tax could be imposed, perhaps as part of the purchase price", and that alternative methods of disposal will have to be thoroughly investigated.

4. POTENTIAL USES OF GTR IN PAVEMENTS

4.1 Introduction

The elastic and adhesion properties of bituminous pavements incorporating GTR may result in pavements that resist rutting and thermal cracking, that have a higher resistance to reflection cracking, and that reduce oxidation, aging and water-induced stripping because they have a relatively thicker binder film. As a result, bitumen-rubber mixes have been advocated for uses such as:

- pavement maintenance
- maintenance hole transition collars
- pavements for high stress environments e.g. at intersections, mountain roads, roads with steep curves, bridge decks, airport runways, and railways
- friction course
- asphalt mixes
- roads prone to ice formation

In pavements, GTR can be used by blending with bitumen or by incorporation in a hot mix asphalt as part of the aggregate fraction. Specific and other uses are outlined in the following Sections 4.2 to 4.8.

4.2 Pavement Maintenance

4.2.1 Crack and Joint Sealing

Blends of bitumen and GTR have been used effectively for filling and sealing cracks in pavements. The bitumen-rubber mixes are found to stick well to the sides of cracks and to remain soft and pliable without bleeding (Bethune 1978). Such products are routinely used by about 80% of state and local highway authorities in the US (Flynn 1992b).

4.2.2 Stress Absorbing Membrane (SAM)

A SAM consists of a sprayed bitumen-rubber binder covered with a layer of aggregate that is compacted by a roller. Rubber particles in the bitumen-rubber are reported to serve as units of "elastic interference to the propagation of cracking" and hence to retard cracking (Singh and Athay 1983). As a result, the treatment layer retards reflection cracking (i.e. cracks in underlying layer show or reflect through the new surface), while it can also reduce longitudinal and transverse cracking caused by thermal fluctuations.

4.2.3 Stress Absorbing Membrane Interlayer (SAMI)

A SAMI comprises a sprayed bitumen-rubber binder that is covered with a layer of hot mix asphalt rather than of aggregate. In this application the bitumen-rubber binder reduces stress caused by reflection cracks, and so reduces the incidence of reflection cracking.

4.3 Maintenance Hole Transition Collars

Because the stiffness of bituminous pavements is different from that of steel maintenance holes or other service installations, the formation of cracks around these road fixtures is common. Over 100 transition collars made by compression moulding of recycled rubber have been installed between steel maintenance holes and the pavement in Toronto. Performance of the installations is reported to be good (MOT of Ontario 1992a,b; Domal Envirotech 1993).

4.4 Pavements for High Stress Environments

Where railways cross roads the high stress environment caused by differences in stiffness between the flexible pavement and the steel rails may lead to early deterioration of asphalt pavements. The use of rubberised asphalt to provide a more flexible joint is appropriate in these crossings.

Rubber asphalt has also been used successfully in other high stress environments such as bridge decks, airport runways, steep curves especially those on mountain roads.

4.5 Friction Course

Friction course is asphalt mix with high void content which, because of its free draining capability, gives good wet skid resistance for vehicles travelling at high speeds, and reduces splash and spray. Its porous nature also produces a low noise surface. Its open nature, however, results in a mix that is not as strong as a normal asphalt mix and allows rapid oxidation of the bitumen, resulting in a reduced life.

Experiments using bitumen-rubber binders near Brussels, Belgium, have shown that their use can achieve increased performance of friction course (OECD 1984).

4.6 Asphalt Mixes

Dense graded asphalt mixes can fail under traffic either by the distress mechanisms of deformation which cause rutting, or through fatigue cracking. In areas subject to large rapid temperature changes, temperature-induced cracking can occur.

GTR has been advocated for use in these mixes to modify the ability of the asphalt mix to resist the above distress mechanisms. The increased flexibility imparted by the rubber can assist in mitigating cracking, whereas the elastic properties combined with increased viscosity at higher pavement temperatures may resist rutting.

4.7 Roads Prone to Ice Formation

The formation of thin layers of ice on pavements causes a dramatic reduction in the skid resistance of the pavement. Where traffic volumes are sufficiently high, the elastic deformation of rubber particles in hot mixed asphalt pavement under traffic loading can initiate the breakup and removal of ice which is further assisted by vehicle-generated wind. An assessment is required of the minimum traffic volume for the deformation mechanism to be effective.

4.8 Other Uses for Waste Tyres and GTR

4.8.1 Noise Barriers

A noise barrier made from 90% recycled rubber has been developed in Canada and was being evaluated in 1992 for its fire resistance and for its use in overall barrier design (MOT of Ontario 1992a, b).

4.8.2 Paving Stones

The MOT of Ontario (1992a, b) reported the commercial development of a paving stone that "looks economically attractive" and is made from a combination of waste tyre rubber, recycled asphalt and waste plastic.

4.8.3 Lightweight Fill/Soil Modifier

The use of GTR for lightweight fill is mentioned by several authors, e.g. MOT of Ontario (1992a, b) and Logsdon (1990). GTR is particularly useful for filling in areas of soft ground, e.g. trench fill.

Ruth (1991) also reports that the University of Wisconsin has conducted research into the use of shredded tyres for fill, with benefits that include the weight reduction of the rubber-soil mixture, conservation of mineral resources, and disposal of the waste tyres.

4.8.4 Energy Attenuators

Whole tyres have occasionally been used to construct energy attenuating barriers at some special sites, such as bridges, piers or tunnel portals, and to provide safety barriers at motor racing events.

4.8.5 Ballast For Construction Markers

Coarse GTR as well as whole tyres have been used to a limited extent as ballast for road construction markers.

4.8.6 Spacers For Steel Guide Rails

Whole tyres have been used as energy absorbing spacers for steel guide rails.

5. COMBINING GTR IN BITUMINOUS PAVEMENTS

5.1 Introduction

The addition of GTR to bitumen may be carried out by one of two quite different processes, the wet and dry processes. In the "wet" process, the GTR is mixed with the bitumen at high temperature for a long enough time to allow the two materials to combine physically and chemically. As the resultant mixture is more viscous than the original bitumen, kerosine or oil is commonly added late in the process to allow the product to be sprayed. Spraying equipment is specially modified for the purpose. The material can be used for seal coats or for hot mixed asphalt.

The alternative "dry" process can only be used in hot mixed asphalt, and consists of adding the GTR to the bitumen and aggregate in the plant mixing chamber. In this process the rubber is held at high temperatures only long enough for it to undergo some initial swelling while it is absorbing the light bitumen fractions. The rubber particles are considered to act as part of the aggregate component rather than as part of the binder.

5.2 "Wet" Process Bitumen-Rubber Pavement

5.2.1 Development of the Wet Process

The wet process was first implemented in Arizona under the direction of Charles H McDonald in conjunction with the Sahuaro Petroleum and Asphalt Company of Phoenix (McDonald 1971), and Altos Rubber Inc. of Los Angeles. The Arizona Refining Company (ARCO) subsequently offered a similar product that used a finer grading of GTR and a premix of bitumen with oil, instead of thinning with kerosine, to temporarily reduce viscosity for spraying purposes. Both processes result in a binder with apparently similar properties.

The McDonald process uses GTR obtained from tyres ground at ambient temperatures and graded so that at least 95% passes a 1.18 mm sieve and less than 10% passes a 0.71 mm sieve. The rubber is blended with bitumen, at 25% by weight at 175-200°C, and continuously mixed until the desired viscosity is achieved. Addition of 5-7% of high boiling point kerosine temporarily lowers the viscosity for spraying.

The specification for the ARCO process is that 100% of the GTR passes the 0.85 mm sieve. The GTR must have a natural rubber component of 20-40%. Mixing of the GTR with bitumen at 18-22% by weight is carried out at 230°C, allowing some degradation of the rubber to produce oil which further reduces the viscosity of the mixture (OECD 1984).

In both processes, blending of bitumen and GTR at an elevated temperature is used to promote chemical as well as physical bonding of the two component materials (Hoyt et al. 1988). The reaction is both time- and temperature-dependent. Pre-blending takes place in insulated trucks or tanks at production temperatures of 175°-230°C. These are higher temperatures than those typically used for applying bitumen (150°C). After pre-blending, the bitumen-rubber mixture is "reacted" at lower temperatures (185°-215°C) for between 30 and 90 minutes. A mixing tank equipped with an agitator ensures that the rubber is evenly distributed throughout the bitumen.

The resultant bitumen-rubber binder increases in viscosity until it reaches a plateau of relatively constant value. If mixing at elevated temperatures is discontinued, degradation of the rubber occurs and viscosity begins to decrease. Optimum mixing time is normally judged to be that time at which the plateau value is achieved, determined by monitoring the viscosity of the mixture (Dickinson 1984).

5.2.2 Characteristics of Bitumen-Rubber Structure

After reaction with the bitumen, the GTR forms a honeycomb network structure through the bitumen. This structure has unique elastic properties different from those of the discrete rubber particles (Bethune 1978).

Many sources in the literature describe the "wet" bitumen-rubber process and its development. Some reports include formulations used on trial sections and an assessment of their performance over a sometimes considerable monitoring period (DSIR (UK) 1962, Bethune 1978, Schnormeier 1980, OECD 1984, Hoyt et al. 1988, Doty 1988, Charania et al. 1991a, Better Roads 1991). In addition, several authors have closely studied the factors influencing the blending of rubber and bitumen by the "wet" process. Reviews of reports by these authors are in Appendix 1 of this report.

The characteristics of the GTR, especially particle size, surface area and chemical composition, are important in determining the required mixing and the properties of the resultant mixture. Details of processes for examining the characteristics of GTR are discussed by Burford and Pittolo (1982) who conclude that chemical composition and surface area are more important than particle size in determining the elastic properties of bitumen-rubber. This conclusion is consistent with the results of testing carried out by Oliver (1982a) who found that particle size was only a minor factor in determining the "reactivity" or degree of bitumen modification obtained with material passing the 1.18 mm sieve.

5.2.3 Factors Affecting Properties of Bitumen-Rubber Binder

The major factors that affect the properties of the bitumen-rubber binder produced by the "wet" process are:

- rubber content
- rubber particle size
- rubber type
- rubber morphology

- blending conditions
- bitumen chemistry
- additive type and quantity

(a) Rubber Content
The quantity of rubber added to the bitumen has a major influence on the properties of the resulting blend. Rubber contents up to 25% are normally used. Higher contents result in a binder with such a high viscosity that it cannot be easily handled.

(b) Rubber Particle Size
As noted in Section 5.2.1 of this report, two particle sizes have normally been used, either 1.18 to 0.71 mm in the McDonald process or less than 0.85 mm in the ARCO process.

Larger particle sizes cannot be used as they would cause practical difficulties in pumping and spraying.

(c) Rubber Type
The percentage of natural and synthetic rubbers in the GTR affects the reaction of rubber with the bitumen. Composition is controlled in the ARCO process by maintaining a natural rubber content of 20-40% of the total rubber. This difference in the properties of bitumen mixtures using vulcanised natural rubber and synthetic rubbers has been noted by several authors (DSIR (UK) 1962, Dickinson 1984, Roberts and Lytton 1987). Consistent properties of a bitumen-rubber blend are obtained only when the relative amounts of natural and synthetic rubbers are monitored and blending times adjusted to suit the different percentages of the two kinds of rubber. Truck tyres have significantly higher natural rubber contents than car tyres, and thus the proportion of tyres from these two sources needs to be controlled.

(d) Rubber Morphology
The morphology or physical characteristics of the rubber particles include the shape and the surface texture. The method of processing the waste tyres significantly affects the nature of the rubber particles and the properties of the resultant bitumen-rubber blend (Burford and Pittolo 1982, Oliver 1982a, Ruth 1992). Grinding the tyres at ambient temperatures is preferred to the alternative cryogenic treatment. The latter, using low temperatures, results in smooth surfaces on the rubber particles and thus a reduction in the area through which the light fractions of the bitumen can be absorbed.

(e) Blending Conditions
High temperature blending is required to accelerate the absorption by the rubber of bitumen fractions which results in the rubber particles softening and swelling. The optimum temperature allows blending to be carried out in a relatively short time, but not to cause degradation of the bitumen. It also has to be below the flash point of bitumen. Optimum temperatures are in the range of 175° to 230°C.

(f) Bitumen Chemistry
The reaction of the rubber with the bitumen is considered to be a partial dissolving of the rubber and also a partial absorption of the oily fraction of the bitumen by rubber particles which undergo significant swelling as a result. The composition of the bitumen affects the degree of dissolution and absorption, the optimum reaction time and the behaviour of the final product (DSIR (UK) 1962, George et al. 1978, OECD 1984).

(g) Additive Type and Quantity
Solvents can be added to the bitumen-rubber blend, either to reduce the viscosity in order that the blend can be sprayed more easily or as a means of increasing the swelling of the rubber particles. The type of solvent, especially its aromatic content, and the quantity affects the properties of the blend.

5.3 "Dry" Process Bitumen-Rubber Pavement

The "dry" process was originally developed during the late 1960s in Sweden by Skega AB and AB Vaegfoerbaettringar, and distributed under the trade names "Rubit" or "Skega Asphalt". This process was subsequently patented in the US under the name "PlusRide". Research and field trials using "dry" process bitumen-rubber blends are summarised in Appendix 2 of this report.

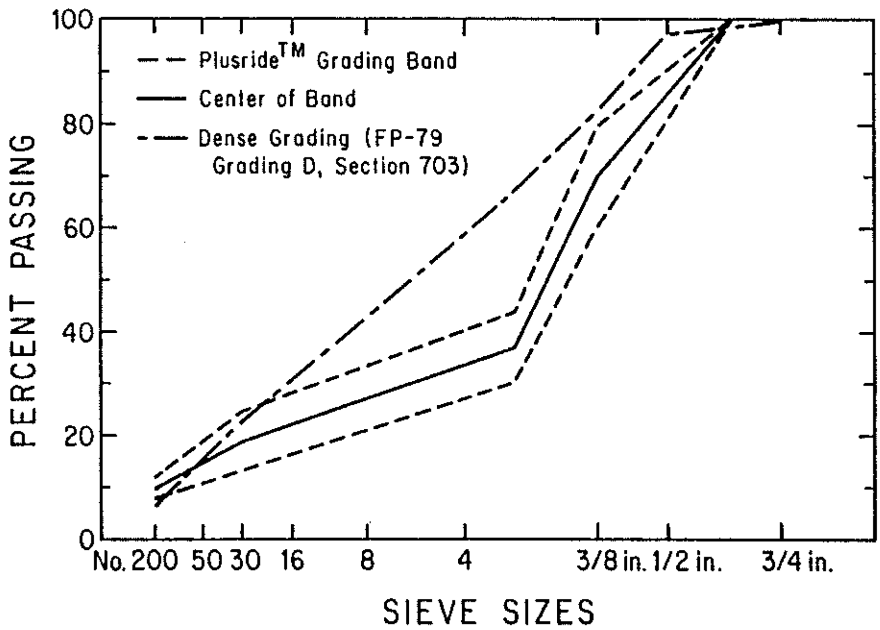

Figure 1. Gradation of PlusRide™ aggregate plotted on a 0.45 power graph (reproduced from McQuillen and Hicks 1987).

The rubber-modified asphaltic concrete is produced by adding up to 3% of mixed sizes of rubber particles directly to the pugmill to replace the 3-6 mm aggregate fraction of a conventional mix. Special grading of the aggregate is required to leave space for these 3-6 mm rubber particles and ensure that the desired compaction is obtained (Figure 1).

The rubber particles, after being in contact with the bitumen, swell and behave as an elastic aggregate in the mix. This process requires the addition of approximately 1.5-2.0% more bitumen than a conventional mix (Takallou and Takallou 1991, McQuillen and Hicks 1987).

A further development of this "dry" process has been carried out by Takallou et al. in 1989 and is called the "generic" process. In this case the mix designs and standards are very similar to those used for conventional asphaltic concrete, i.e. special grading of the aggregate is not required. The generic process uses 3% by weight of rubber with a grading designed to be compatible with a specific dense graded aggregate mixture.

The mixing times for both the PlusRide and generic processes are short (approximately 15 seconds) to allow swelling of the rubber particles but not to allow dissolution of the rubber in the bitumen.

Mixes are laid at the normal temperatures used for asphalt mixing ($\approx$150°-160°C) using conventional equipment equipped with vibratory screens to assist compaction. Steel drum rollers are normally used, with provision for spraying water containing soap or detergent onto the roller drum if the mix is sticking to it. Pneumatic rollers are not recommended.

6. MODIFYING BITUMEN PROPERTIES BY ADDING RUBBER

6.1 Introduction

The primary objective in mixing rubber with bitumen is to impart some of the elastic and adhesive properties of the rubber to the resulting blend to improve the performance of pavements. Although bitumens and rubbers have sufficient chemical similarities to allow them to be combined effectively by using elevated temperatures, the mechanism by which this occurs is complex and not fully understood.

Bitumen properties are modified differently by adding either "pure" (natural or synthetic) rubbers or GTR. The addition of even small percentages of GTR to hot bituminous binder significantly alters the properties of the material. The magnitude of the changes in properties is dependent on such things as the degree of absorption of light bitumen fractions by the rubber which in turn is a function of the rubber particle size and surface area, the bitumen temperature and the mixing time.

The main properties of the bitumen which are altered are:

- **Absolute viscosity** - this increases with the percentage rubber content. If temperatures or storage times are excessive, the viscosity may subsequently decrease as rubber degradation occurs.

- **Softening point** - this is raised by the addition of rubber. Vulcanised rubber generally has a lesser effect on the softening point (which thus is lower) than other rubber types.

- **Penetration of bitumen** - this test is a measure of the hardness of a bitumen at 25 °C. The penetration value is almost always reduced by the addition of rubber, i.e. the bitumen-rubber blend is harder at 25 °C.

- **Temperature susceptibility** - the rate of change of viscosity with temperature is reduced with the addition of rubber.

- **Elasticity** - the addition of rubber imparts an elastic component to bitumen.

6.2 Assessing Properties of Rubber-Modified Bitumen

Many researchers have recognised the difficulties in evaluating the deformation and flow properties of bitumen-rubber blends. Empirical methods traditionally used to define the properties of the constituents are not generally satisfactory for assessing the resulting blends because they have properties that are intermediate between the rubber and bitumen.

Procedures for the laboratory production of bitumen-rubber blends to be used to assess mix design are suggested by Roberts and Lytton (1987). They also provide information on the recommended methods for evaluating the materials produced.

Methods for determining the proportions of synthetic and natural rubber in the bitumen-rubber blends for quality control purposes are given by several authors including Salomon et al. (1954), DSIR (UK) (1962), Linde (1987), Malek (1984), Szatkowski (1963), and Oliver (1982b).

The characterisation of GTR is discussed by Burford and Pittolo (1982) who used either a scanning electron microscope or an optical stereo-microscope to examine the surface features, and additional analytical equipment to measure particle surface area. The chemical composition of GTR samples was assessed by means of gas chromatography. Elasticity measurements were made on different bitumen-rubber blends.

7. USE OF GTR FOR PAVEMENTS IN NEW ZEALAND

7.1 Introduction

GTR can be used blended with bitumen in the "wet" process either as a chipsealing binder or as the binder in a bituminous mix. It can also be used in the "dry" process in a bituminous mix when incorporated as part of the aggregate feed in a hot mix plant.

GTR can be used in road pavements in New Zealand, using either wet or dry processes, and in both chipsealing and bituminous mixes.

A number of benefits can result from the use of GTR, and these also apply to natural and synthetic rubber additives. The benefits include:

- Increased flexibility which can lead to increased life of the chipseal or bituminous mix before cracking will occur;
- Increased strength which can lead to better performance of chipseals in high traffic stress areas;
- Decreased temperature susceptibility which will inhibit deformation of bituminous mixes at high pavement temperatures but still allow good performance at low temperatures;
- Reduced winter maintenance, increased skid resistance, and reduced wear.

The above benefits would be expected to result in an increase in the life of the pavement layer over that obtained using normal bitumen as the binder.

In some cases where pavements have deteriorated to the point that total replacement is the usual option, surfacings using bitumen-rubber have significantly extended the life of the damaged pavement and allowed a large capital expenditure to be deferred for several years.

Barriers to the introduction of GTR are:

- costs
- GTR production
- special plant requirements
- environmental factors
- recycling bitumen-rubber pavements
- performance of pavements

7.2 Costs of Bitumen-Rubber Pavement

Bitumen-rubber pavements, either as chipseal or as bituminous mix, are most commonly reported to have an in-place cost that is 40-100% higher than conventional pavements. These costs provide a comparison of the initial capital cost, relative to conventional pavements. They do not generally include the difficult assessment of the expected lifetime cost of the bitumen-rubber pavement which would include the expected decrease in annual maintenance costs, increased skid resistance, etc.

Currently an increase in construction of bitumen-rubber pavement trials internationally is being driven by environmental requirements. Since techniques for construction of bitumen-rubber pavements continue to evolve, data to assess possible lifetime benefits will become available only when the results of long-term monitoring of recently constructed trials are analysed.

The cost effectiveness of the bitumen-rubber pavements is critically dependent on the increased life, decreased maintenance, and reduced layer thickness of these pavements relative to a conventional pavement of comparable performance. Details of cost studies are summarised in Appendix 3 of this report.

In New Zealand, roading authorities are very cost conscious, and thus the use of rubber is restricted to areas only where a bitumen-based material would not perform as well, e.g. in chipseals where the traffic stresses would immediately remove chips. This cost consciousness is expected to continue, and thus bitumen-rubber will continue to be used only in special situations.

7.3 GTR Production

Experience from the US indicates that the economics of tyre recycling for GTR production by shredding and crumbing only became viable after the regulatory environment began to change in the mid 1980s.

Similarly in New Zealand, the driving force to initiate introduction of new waste disposal practices is likely to arise from regulatory or legislative change such as those concerning the Resource Management Act (NZ Government 1991). Any legislation which would affect the cost or viability of landfill disposal of tyres would markedly change the economics of recycling tyre rubber.

Even with a supportive regulatory framework, transportation costs and guarantee of supply are significant factors in determining the economics of tyre recycling. For example, in 1985 a large tyre processing firm in the US made far more revenue from their tyre acceptance fee than from the sale of their end product which was mainly a fuel for cement manufacturing or for power generation. This trend was expected to continue until energy costs increased (Grady 1987).

To produce a consistent standard of rubber to use with bitumen in pavements, the tyre recycling operation would have to maintain a controlled ratio of truck to car tyres (see Section 5.2.3(c) of this report). The operation also needs to produce consistent particle shape and morphology of the rubber crumbs by controlled gradation and processing conditions. These requirements increase the cost of production.

European data indicates that the cost of GTR to produce is about NZ$1,500 per tonne (Bebbington 1991), while in Australia rubber recycled at the new Pacific Dunlop facility in Melbourne, will cost about NZ$950 per tonne to produce (Nixon 1992).

7.4 Special Plant Requirements

The specialist equipment required for the production by the "wet" process is summarised by Takallou and Takallou (1991).

The specialised equipment used in production and proportioning ..... includes:

1. *An asphalt heating tank with a hot oil heat transfer system or retort heating system capable of heating asphalt cement to the necessary temperature for blending with the granulated rubber. This unit normally is capable of heating a minimum of 3,000 gallons of asphalt cement**.

2. *An asphalt-rubber mechanical blender with a two stage continuous mixing process capable of producing a homogeneous mixture of asphalt cement and crumb rubber at the mix design specified ratios. This unit must be equipped with a crumb rubber feed system capable of supplying the asphalt cement feed system so the continuity of the blending process is not interrupted. A separate asphalt cement feed pump and finished product pump are required. These units have an asphalt cement totalising meter, in gallons, and a flow rate meter, in gallons per minute.*

3. *An asphalt-rubber storage tank. This tank is equipped with a heating system to maintain a proper temperature for pumping and adding the binder to the aggregate, and an internal mixing unit within the storage vessel capable of maintaining a proper mixture of asphalt cement and crumb rubber.*

4. *An asphalt-rubber supply system equipped with a pump and metering device capable of adding the binder by volume to the aggregate at the percentage required by the job mix formula.*

To spray the bitumen-GTR blend for chipsealing treatments, specially modified distributors are required. The high viscosity particulate nature of the resulting binder requires a distributor equipped with a stirring system to keep the rubber in suspension plus special nozzles to obtain an even coverage.

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* This volume is in American gallons and is equivalent to 11,500 litres.

The laying of "wet" or "dry" process GTR-asphalt may be carried out with conventional paving machines equipped with full width vibratory screens to aid compaction. Compaction using conventional steel rollers with a fully operational water spray system containing some soap or detergent to prevent pickup of the material on the rollers is recommended. Pneumatic tyre rollers are not generally suitable (McQuillen and Hicks 1987, Takallou and Takallou 1991).

7.5 Long-Term Environmental Factors

An environmental assessment of the production of GTR rubber for asphalt has been carried out by the Florida Department of Transportation and reviewed by the Florida Department of Environmental Regulation, Bureau of Air Regulation. Data were obtained from trial pavements constructed during the period 1989-90.

Results of air quality monitoring showed no significant difference in emissions during production of either conventional asphalt or asphalt rubber. The use of asphalt rubber friction course and SAMI interlayers in Florida has been approved by the Florida Department of Environmental Regulation. However, prolonged heating at high temperatures should be avoided as degradation of the GTR may release sulphur dioxide and asphalt volatiles (Ruth 1992).

In Ontario, Canada, leachate analysis of rubber chips designed for embankment fill shows that although small quantities of metals are in the leachate, the rubber remains essentially inert. Clearance with the Ontario Ministry of the Environment was being sought in 1992 for use of granulated tyre rubber as fill (MOT of Ontario 1992a, b). This inert behaviour is also recognised by the United Nations and Economic Commission for Europe who both note that tyre rubber is *"..... not affected by weather or putrefactive or bacterial processes"* (ECE 1985).

Further information regarding environmental effects of using scrap rubber in road construction will become available after June 1993 when the US Environmental Protection Agency is required to report on the matter to Congress. Full findings are expected at a later date (Flynn 1992b).

7.6 Recycling Bitumen-Rubber Pavements

Information concerning the viability of milling and recycling old bitumen-rubber hot mix pavements is lacking. While some engineers in the US believe that use of rubber will create problems, the study in Florida (Ruth 1992) suggested that recycling pavement would not be a problem since the overall rubber content of the pavement would be low.

7.7 Performance of Pavements

An enhanced performance of pavements is obviously required from the use of GTR. An appreciation of the benefits under New Zealand conditions can only be obtained through the construction of field trials and the commitment of roading contractors to gain experience in blending and handling bitumen-rubber binders.

GTR-based pavements would appear to be potentially more variable in their properties than those using natural rubber. Close control on GTR properties and in blending and handling would be required in order to ensure consistent performance.

7.8 Current New Zealand Use of Rubber in Pavements

7.8.1 Forms of Rubber Used

Currently (1995) in New Zealand two forms of rubber are used in bitumen-rubber blends for pavement construction. They are natural rubber and SBS-rubber.

Natural rubber is added to bitumen in the form of latex at concentrations up to 1%. This material is used in chipsealing in higher stress pavements, e.g. at intersections; and over lightly cracked pavements.

SBS copolymer is added to bitumen for chipsealing pavements in such similar situations as well as for crack sealing, SAM, and SAMI applications. In New Zealand SBS is used in chipseals but not in asphalt mixes (as it is in other counties). The only known use has been on the Auckland Harbour Bridge where both natural rubber and SBS have been used.

Natural and SBS rubbers can be used with conventional equipment. They are also consistent in their properties. SBS polymer, when added at concentrations of approximately 5% or greater, forms a network through the bitumen, and the resultant material has properties more akin to rubber than bitumen.

7.8.2 Costs of Rubber Used

SBS rubber is sold as a concentrate in bitumen or as a pre-blended hot binder. The concentrate has a polymer content of 20% and currently retails at approximately $4,400/tonne, compared to bitumen which costs only approximately $550/tonne.

In chipsealing, the increased cost using an SBS-modified binder (with a polymer concentration of about 4%) is typically in the order of 40-80% greater than the cost of a conventional chipseal. The binder cost is about doubled if 4% SBS polymer is used. (Costs of natural rubber or GTR used in New Zealand were not available at the time of the review.)

Exact figures of the quantity of rubber-modified bitumen being used in New Zealand are not available, but it is estimated that it comprises less than 5% of the total 100,000 tonnes of bitumen used annually.

7.9 Potential New Zealand Use of GTR in Pavements

The potential uses for GTR in New Zealand pavements cover all those listed in Section 4 in this report. However, for pavements and mixes, the major potential use is considered to be in asphalt mixes and friction course, using the dry process.

The use of GTR in the wet process requires specialised plant for the blending, storage and application of the binder. The costs associated with this specialised plant, and the fact that this plant has to be close to the area of use, may result in a product that is significantly more expensive than the rubber materials currently used.

For applications where relatively small quantities of bitumen are used (e.g. crack filling), pre-blended blocks of material that can be heated on site and applied with small specialised plant are currently used. These appear to be cost competitive.

In the dry process, GTR is added as part of the aggregate fraction. The work carried out in other countries has tended to use asphalt plants equipped with a pugmill. The effect of a drum mixing plant (the kind commonly used in New Zealand) on mixing is unclear but no major difficulties are foreseen. Plant modification to incorporate GTR would appear to be minimal. The dry process is not restrained by storage time restraints and therefore could be relatively easily used throughout New Zealand.

If GTR is added to a bituminous mix, the cost of the mix is increased by the cost of the rubber and the extra bitumen required. The justification for its use would be based on an increased life or a reduction in layer thickness, resulting in a reduced cost per square metre.

As at 1993 New Zealand practice tended towards using thin pavement layers of 25-30 mm. Little scope for further reduction in layer thickness using these current laying and compaction techniques was considered possible. On new pavements the increased fatigue resistance could justify thinner basecourse layers. It is considered, however, that information is insufficient on the properties of the mixes produced using the dry process, to confidently perform detailed pavement designs.

Justification for the use of GTR would be expected to be based on the expected increase in the life of the rubber-modified pavement. If New Zealand costs are similar to those given for costs in other countries in Appendix 3 of this report, then the mix would be in the order of 50% dearer than conventional materials. Where the underlying pavement is cracked or in an area of high deflection, then the bitumen-GTR could be cost effective.

GTR would be competing with polymer-modified bitumens for use in cracked pavements. As stated in Section 7.8, very little use had been made of asphalt mixes modified with rubber in New Zealand before 1995.

8. CONCLUSIONS

This review of the potential use of waste tyre rubber as GTR in New Zealand pavements has concentrated on its use in bituminous road pavement surfacings. The main findings are:

1. The two main processes to incorporate GTR in pavement surfacings are:
    - Wet process - where GTR is blended with hot bitumen and applied as a sealing binder or used in an asphalt mix;
    - Dry process - where GTR is added to the aggregate in the production of hot asphalt mixes.
2. The wet process used currently is not expected to be cost-competitive with the SBS-based binders because:
    - The total volume of GTR used is not sufficient to justify the capital expenditure on:

      - the specialised mixing plant which is required near a construction site because the blended binder has a limited storage life;

      - the specialised distributors which are required to spray the binder, and which can cope with both its high viscosity and the rapid segregation of the bitumen and ground rubber.
    - The cost difference between GTR and SBS is also not sufficient to justify the above capital expenditure, as follows:

      - Cost of GTR is expected to be at least NZ$1,000/tonne (as at 1993) because the proportion of truck to car tyres needs to be controlled, and the grinding and sieving of the tyre rubber needs to be to a relatively narrow size grade range;

      - 20-25% (five times more) of GTR is required to produce a binder with similar performance properties to those obtained in a binder containing only 4-5% of SBS.
3. GTR has a potential use in asphalt mixes produced by the dry process, if the rubber can be easily included as part of the aggregate feed system in a drum mixing plant.
4. If GTR is used in asphalt mixes, using concentrations and aggregate gradings similar to those used in other countries, the cost of the mix could be expected to increase by approximately 50%.
5. The higher cost of GTR mixes would tend to restrict use of these mixes only to special situations where the enhanced performance would result in lower discounted costs than alternatives such as reconstruction.
6. In maintenance treatments, such as crack and joint filling or around maintenance hole covers, pre-blended bitumen-GTR appears to be cost competitive with other rubbers.

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APPENDIX 1

REVIEWS OF LITERATURE ON "WET" PROCESS RUBBER-MODIFIED ASPHALTIC CONCRETE

REVIEWS OF LITERATURE ON "WET" PROCESS RUBBER-MODIFIED ASPHALTIC CONCRETE

A1.1 Introduction

The main findings of reports dealing with "wet" process bitumen-rubber blends are presented below in chronological order of publication, from most recent to oldest.

A1.2 Reviews of Reports

Ruth, B.E. 1992. Evaluation of ground tire rubber in asphalt concrete : final report. ***Florida Department of Transportation Project No. 99700-7520-010,*** **January 1992. 58pp.**

Ruth (1992) presents a report on a comprehensive evaluation of ground tyre rubber (GTR) in bitumen. The evaluation was carried out by the Florida Department of Transportation (DOT) in response to US legislation passed in 1988 that required such studies to be undertaken. Use of asphalt-rubber for seal coats and interlayers as well as for joint sealing and railway crossings was already permitted in Florida following a study carried out in 1980.

Florida DOT consider that, since 85% of all asphaltic concrete hot mix in Florida contains about 35% of recycled asphalt pavement, the addition of GTR to this material is not appropriate as it would interfere with the rejuvenation of the old binder. Instead they consider that the asphalt-rubber should be used in friction course mixtures. The increase in viscosity with addition of GTR to asphalt leads to improved aging because of antioxidants in the GTR. Also the greater film thickness reduces oxidation. It also improves elasticity/resilience which may improve aggregate retention and reduce shoving at major intersections.

A literature review completed in 1989 by Florida DOT (Ruth 1989) detailed material properties, benefits, limitations and recommendations for the use of GTR and asphalt-rubber binders. The review also showed that basic research on the interaction of GTR with asphalt was lacking.

During 1989 and 1990 projects were constructed to assess GTR in three asphaltic concrete mixes, one of which was dense graded and two were open graded. The dense graded mix was most sensitive to binder content and GTR mesh size.

In the first project, testing of hot mix samples of dense graded pavement showed that a GTR content of 5% by weight of total binder seemed to be the optimum rubber content. The mix with 10% GTR had lower density and shear values, and also tended to stick to the paver screed during its placement. No other significant problems were encountered during construction.

The second project consisted of open graded asphalt with test sections containing between 5-17% GTR by total weight of binder. Construction was without problems. Results of testing showed that 10-15% GTR can be used but that total binder content should probably be less than used on this project because hydroplaning by vehicles and long-term performance problems are possible. However, no problems had been observed after 30 months of monitoring. Preliminary laboratory testing to determine GTR-asphalt blends and mix designs was of primary importance to both the first and second projects.

The third demonstration project was constructed on Interstate 95 with 10% GTR content to test a prototype production blending unit. No major technical problems were encountered but the production temperature was lower than anticipated (275°C v 315°C). This slowed down blending since the time to provide adequate reaction of the GTR with the asphaltic cement was increased.

The conclusion drawn from all three demonstration projects is that use of GTR in asphalt is feasible without having to make major changes to the construction operation. Long-term data are not yet available, but indications are that bitumen-rubber friction courses have greater long-term durability than conventional mixes. The durability is a result of reduced age hardening caused by antioxidants in the GTR and by increased film thickness. It also is a result of improved retention of aggregate arising from the greater film thickness and resiliency related to higher viscosity resulting from the addition of the GTR.

All literature, laboratory and demonstration project information was combined with more recent data to produce a set of initial specifications to serve as guidelines for Florida DOT for construction projects. These specifications are included in an appendix to their report. Modifications to the specifications may have been made after observations have been collected during the 1992 and 1993 seasons.

Because the ASTM (1980) defines "Asphalt-Rubber" as containing a minimum 15% GTR and the demonstration project mixes contained a lower percentage of GTR, the term "Rubber-Modified Asphalt Binder" is used in the Florida DOT specifications.

Ruth's report includes tabulated details of the performance data for the three demonstration projects. Friction values were measured on all the asphalt-rubber test sections and conventional asphalt control sections. All test sections on the dense graded demonstration project were performing very well with respect to friction. The open graded demonstration project sections were also performing well though the ride on the second demonstration project is not as good as that on the third project (Interstate-95) where ride is the same for the asphalt-rubber and the control sections. The surface texture on Interstate 95 is also visually very uniform.

Density of the test sections was monitored and no increase in density was recorded over a 24 month period for sections with similar binder contents. A 5% increase was recorded on one section of the second demonstration project which had a high binder content of 8.2%. This, and a GTR content of 11.4%, probably created a greater than normal initial resistance to compaction. Indirect tensile strength was also less, as a result of decreased binder viscosity arising from a 5% extender oil content.

Blending, storage and transport of the asphalt-rubber mixtures was accomplished with no major problems. Experience gained from the projects indicates that temperatures above 180 °C should not be used because of degradation of GTR and consequent softening of binder. The procedure used was the addition of GTR to hot asphaltic cement, followed by mechanical mixing, to provide uniform dispersion of the rubber in the asphalt. The asphalt-rubber binder then comes to equilibrium once the absorption of the asphalt light fractions has taken place. Blending time depends on fineness of the GTR and the temperature, and is assessed by monitoring the viscosity to determine when a uniform mix is achieved. Overblending or excessive temperature degrades the quality of the asphalt-rubber binder.

After laboratory tests had showed that GTR finer than No. 30 sieve required only 10-15 minutes mixing at 163 °C, the Interstate 95 demonstration project was designed to verify this blending process at full scale. The objective was to show that terminal blending, and then transporting to the hot mix plant, was feasible, rather than blending at each hot mix plant, in order to find ways to decrease the need for specialised blending equipment and improve quality assurance. A mixture of 12% GTR was blended at 163 °C and then stored at 140-160 °C for four days. Viscosity monitoring showed no decrease that would indicate softening was occurring caused by breakdown of the GTR. Such decreases had been reported by other researchers at higher storage temperatures (over 180 °C). Storage temperatures needed to be slightly higher for higher GTR content mixtures and consequently low GTR content asphalt-rubber blends store better because the temperature decreases during transport. Agitation is required to prevent separation of the GTR from the binder in all blend concentrations.

After assessing suitable preparation methods for the crumb rubber, grinding to suitable fineness at ambient temperatures was recommended. Cryogenic treatment is not acceptable as at 1992 because it produces smooth surfaces that reduce the surface area for absorption of light fractions of asphalt. Also the effect on blending time and properties of the resultant asphalt-rubber were not evaluated by the Florida DOT. The optimum amount and fineness of the GTR used in asphalt-rubber were found to depend on the application.

For dense graded friction course, a 5% GTR content by weight of asphaltic cement, passing a 0.18 mm sieve (a nominal 80 mesh), is recommended.

For open graded friction course a maximum of 12% GTR, passing a 0.25 mm sieve (a nominal 60 mesh), is recommended. These open graded mixes are more tolerant of larger GTR particle size (up to maximum 0.6 mm). Some uncertainty concerns the long-term performance at higher GTR contents, particularly in heavily trafficked areas.

The use of asphalt-rubber binders in stress-absorbing membrane interlayers (SAMIs) is discussed. In this use the asphalt-rubber mix includes 20% by weight of GTR passing the 2 mm sieve and is sprayed at the rate of about 0.6 gal/yd^2. Larger particles and higher percentage of GTR may be used with higher blend temperatures (up to 190°C) since the storage time is short. It is, however, still considered better to blend at 170°-177°C or use finer GTR.

Research is recommended by Florida DOT to develop a "sprayability" test at blend temperatures of 165°C and 177°C, to determine the required nozzle characteristics and pressure requirements. Determining the best parameters with which to assess the performance of the SAMI was also considered desirable.

An environmental assessment of the Florida DOT production processes revealed no problems with atmospheric emissions unless either extended heating or excessive temperature were used. In those cases GTR may degrade yielding sulphur dioxide and asphalt volatiles. If recommended practices are followed, the emissions during placement of asphalt-rubber were not different from those during placement of conventional asphalt.

The appendices (A to F) to the Florida report contain specifications and test methods.

Charania, E., Cano, J.O., Schnormeier, R.H. 1991a. Twenty year study of asphalt rubber pavements in Phoenix, Arizona. *Transportation Research Record 1307*: 29-38.

Charania et al. (1991a) describe the results of 20 years study of the use of asphalt-rubber pavements in Phoenix, Arizona, where use of the material began in the early 1960s. Details of the early trials are given and problems that arose are noted.

Guidelines and specifications developed to achieve satisfactory performance are summarised, and information concerning viscosity and its effect on the aging of pavements is presented.

Detailed observations of all streets in Phoenix where asphalt-rubber surfaces were still in service are discussed, and the use and advantages of asphalt-rubber considered.

The early formulations of asphalt-rubber chipseals have been replaced by an equally satisfactory asphalt-rubber asphaltic concrete because of public opposition to the damage caused by loose chips to cars. The new mix design and its advantages are discussed. Details of this design are available only on applying to the authors although details of the chipseal design used earlier are given in the report.

Doty, R.N. 1988. Flexible pavement rehabilitation using asphalt-rubber contaminations: progress reports. ***Transportation Research Record 1196*****: 212-223.**

Doty (1988) describes the construction and performance assessment of several trial sections of ARCO asphalt-rubber pavement carried out by the California Department of Transportation in 1983. Three PlusRide pavement sections were also constructed. The asphalt-rubber section comprised combinations of dense graded asphaltic concrete with and without SAMI as well as SAM and double layer SAM, using a product from the ARCO and McDonald/Sahuaro processes. Some details of pavement as-built properties are given (in their Appendix 1).

Monitoring of the pavement performance is discussed though final conclusions as to the lifetime of the rubberised pavements will be determined only after further monitoring. The conventional asphalt pavements had failed during this monitoring period even though, as noted by the author, standard design practice for these road sections allowed for thick 210 mm conventional overlays rather than the thinner overlays used for these trials. This result in itself indicates that the rubberised pavements may be expected to outperform a conventional pavement of the same thickness and that layer equivalence is an important consideration in assessing the cost of the rubberised pavement.

Hoyt, D.M., Lytton, R.L., Roberts F.L. 1988. Performance prediction and cost effectiveness of asphalt-rubber concrete in airport pavements. ***Transportation Research Record 1207*****: 88-99.**

Hoyt et al. (1988) describe a laboratory evaluation of the properties of asphalt-rubber, produced by the ARCO process, to predict the performance of the material in terms of rutting, cracking and lifetime when applied to airport runways in each of four climatic zones in the US.

Parameters measured in the laboratory included fatigue characteristics, fracture properties, creep and permanent deformation. Asphalt-rubber concrete samples with optimum binder content and with optimum ±0.5% binder content were prepared to assess the sensitivity of the mix designs to slight variation in the binder content. The parameters were used in a pavement analysis program (ILLIPAVE), together with a suitable structural model, and suitable environmental and loading conditions. The data from the analysis allowed Hoyt et al. to estimate predicted damage from cracking and rutting over a 20 year period. This information was then used to evaluate the cost effectiveness of each type of pavement based on its expected life. In three of the four climatic zones, the use of asphalt bitumen-rubber pavements at low to medium binder contents (4.23-5.23%) was found to be more cost effective than conventional asphalt with 4.8% binder.

Linde, S. 1987. Degradation of styrene-butadiene-styrene elastomers (SBS) in bitumen blends at elevated temperature. ***Swedish National Testing Institute Technical Report 1987:29.*** **27pp.**

Linde (1987) reports on the evaluation of two laboratory methods used to determine the SBS content of asphalt-rubber mixtures to assess the degradation of the rubber at high temperatures. The gel permeation chromatography (GPC) and thermo-mechanical analysis methods are applied, in this case to the analysis of a synthetic rubber.

McQuillen, J.L., Hicks, R.G. 1987. Construction of rubber modified asphalt pavements. ***Journal of Construction Engineering and Management 113(4):*** **537-553.**

McQuillen and Hicks (1987) discuss operational details of the ARCO process including recommended types of asphalt, rubber and aggregate gradings, production, laying and compaction. By means of a questionnaire they also attempted to evaluate construction practices. Comments indicated that the increased cost of this type of mix arises primarily from the incorporation of the rubber with the asphalt and is not related to aggregate grading, laying practices, or to a high risk perception by contractors.

Roberts, F.L., Lytton, R.L. 1987. FAA mixture design procedure for asphalt-rubber concrete. ***Transportation Research Record 1115*****: 216-225.**

Roberts and Lytton (1987) developed a design procedure for the use of asphalt-rubber binders made from GTR for flexible airport pavements. The work was carried out on behalf of the US Federal Aviation Administration (FAA), and includes information on laboratory tests for characterising asphalt-rubber, the effects of rubber types, processing and concentration on the overall properties of the mixture, and the effects of reaction time and mixing time. Laboratory procedures for producing and evaluating asphalt-rubber mix designs are outlined in detail, including examples of their own test materials and the evaluation of the test results.

Dickinson, E.J. 1984. ***Bituminous roads in Australia.*** **Australian Road Research Board, 300pp.**

Dickinson (1984) contrasts the elastic and flow properties of rubber and bitumen with data showing the dependence of viscoelastic response on temperature and the effect of the addition of two types of rubber on the bitumen properties.

An experimental method for assessing the elastic recovery of bitumen-rubber samples is described and illustrated using data from the two samples.

A discussion of the different effects of the rubber crumb preparation method points out that brittle fracture of frozen rubber produces a crumb with relatively smooth surfaces and low surface area that is not as suitable for use with asphalt. Interaction with asphalt is much more effective when the crumb is produced by dry grinding at ambient temperatures producing particles with *"surfaces covered with porous sponge-like nodules"*.

Oliver, F.W.H. 1984. The laying of the second scrap rubber modified bitumen road trial. ***ARRB Internal Report AIR 286-9*****, September 1984.**

Oliver (1984) gives details of the placing of a trial section for the Australian Road Research Board (ARRB), to assess the effect of rubber particle type and rubber concentration on the ability to retard reflection cracking. Details of the materials used, the condition of the site, construction details, and sampling and testing procedures are discussed. Monitoring of the site was to continue.

OECD Scientific Expert Group 1984. ***Road transport research : road binders and energy savings.*** **OECD, Paris, 181pp.**

OECD Scientific Expert Group (1984) outline the basic features of the McDonald and ARCO processes and also describe briefly the use of SAMs and SAMIs. They include recommendations for surface preparation, binder application rates, and aggregate size and aggregate application rates. A summary of design and placement recommendations for open graded and bituminous concrete wearing courses is also given.

Singh, J., Athay, L.D. 1983. Technical, cost and institutional aspects of asphalt-rubber use as a paving material. ***Conservation and Recycling 6(1/2):*** **21-26.**

Singh and Athay (1983) describe typical reasons for the failure of asphalt pavements and then discuss the application and value of SAMs and SAMIs in reducing the incidence of pavement failure. Rates of application and temperatures are outlined.

Comparing costs with conventional asphalt is considered difficult because the alternatives are not well defined, the lifetimes of the asphalt-rubber surfaces are not known, possibilities for reducing future maintenance are not quantified, and the value of deferring capital expenditure for major reconstruction requires consideration.

The estimated initial cost of a SAM is 45% more than for a conventional chipseal though the authors consider it likely to be cheaper in the long run. The initial costs of a SAMI are considered to be much lower than the alternatives of reconstruction or thick overlay.

Because the properties of the asphalt-rubber are sensitive to the rubber composition, the overall quality of the mix may vary depending on the type of tyre from which the crumb rubber is made.

The effect of environmental rules limiting US Federal funding to pavement applications of asphalt mixes thicker than 20 mm is claimed to discourage state authorities from using thin SAM surfaces which may not qualify for funding. Instead the effect may encourage applying a more expensive SAMI plus overlay, for which their own expenses are less because a SAMI overlay attracts federal funding. Brief discussion of environmental problems posed by waste tyres includes the opinion that government policies and incentives are the key to solving the disposal problem.

Interesting figures on the energy savings from using asphalt-rubber, based on the replacement of 20-25% of the asphalt by rubber, indicate that savings of 20,000 to 90,000 Btu per sq yard may be achieved with SAM applications and almost 120,000 Btu per sq yard for SAMI applications. The details of the calculations are not included in the report.

Schnormeier, R.H. 1980. Eleven year pavement condition history of asphalt-rubber seals in Phoenix, Arizona. Asphalt Pavement Construction : New Materials and Techniques. ***ASTM Special Technical Publication 724*** **(J.A. Scherocman Ed.): 13-21.**

Schnormeier (1980) reports on the use and performance of asphalt-rubber seals in Phoenix, Arizona, over an 11 year period. The work describes the sites at which trials of asphalt-rubber were carried out. Because of the cost of the material, all were sites where deterioration had progressed to the point where correction with conventional seals was not possible. The performance of the asphalt-rubber pavements after 11 years was considered most satisfactory, particularly because it led to a significant reduction in the maintenance that was required.

This report complements the reports of Charania (1991a,b) which review the performance of the same pavements after a further 11 years.

Vallerga, B.A., Bagley, J.R. 1980. Design of asphalt-rubber single surface treatments with multi-layered aggregate structure. Asphalt Pavement Construction: New Materials and Techniques. ***ASTM Special Technical Publication 724*** **(J.A. Scherocman Ed.): 22-38.**

Vallerga and Bagley (1980) present the details of four test sections of pavements in Phoenix, Arizona, comprising heavy applications of asphalt-rubber binder (1.86-8.87 ℓ/m^2) and aggregate (13-37 kg/m^2) to form a multi-layered aggregate structure. A conventional asphalt control section was placed for comparative purposes.

Construction details are discussed, including heating and circulation systems for the distributor truck, and provision for a spreader bar equipped with nozzles capable of delivering the asphalt-rubber at the required rate. The authors recommend pressures of 60-80 psi with Etnyre S36-5 nozzles for spraying asphalt-rubber mixes with a viscosity up to 2 Pas (2000 cP). Satisfactory performance of this type of surface is primarily dependent on a correct balance between the asphalt-rubber binder and the aggregate.

Conventional design methods, which assume that a single layer is of half embedded chips, were found to be inapplicable. So a new design method to determine the asphalt and aggregate application rates required to achieve a given layer thickness was derived and is included in the report. The performance of the pavements constructed using this new design procedure was considered to be excellent.

Bethune, J.D. 1978. Use of rubber in bituminous surfacing. ***ARRB Proceedings 9(3):*** **157-181.**

Bethune (1978) presents a report which outlines the development of asphalt-rubber in Arizona, USA, and the experience of the Victorian Country Roads Board (CRB), Australia, in using these materials for constructing several trial sections of pavement. The author had visited Arizona, and so discusses the construction and assessment of trial sections carried out by the Arizona Department of Transportation. Details of the reaction between the asphalt and rubber are included along with an overview of factors that influence the reaction and the optimal rubber content in the mixes.

The CRB procedures are described and an outline of further research work to be undertaken is given. The appendix to their report contains details of the CRB experimental sections including the site, normal design application and ADT (average daily traffic), the average application rate of modified binder, the aggregate size and any relevant comments.

George, J.D., Piggott, M.R., Woodhams, R.T. 1978. ***Recycling of scrap tires to improve pavement asphalts.*** **University of Toronto, Toronto, Ontario, Canada, May 15 1978.**

George et al. (1978) present the results of research carried out by the University of Toronto, Canada, that investigated the use of GTR in asphaltic concrete. The work included laboratory and field measurements to determine suitable mix designs for their trials. The 15 mixes used contained a maximum of 1.4% rubber and were prepared by either "wet" or "dry" processes. Precise details of the production temperatures, etc., are not given. For practical reasons related to the available equipment, they decided to restrict use of the rubber to "dry" process rubberised asphalts. The laboratory test data include graphs showing flexural strength as a function of temperature, stress-strain curves, load deflection curves for samples with and without rubber, and viscosity as a function of rubber content and time.

Green, E.L., Tolonen, W.J., Dunning, R.L. 1977. The chemical and physical properties of asphalt rubber mixtures. ***Arizona Department of Transportation Report ADOT-RS-14 (162)*****, Final Report Part 1 - Basic Material Behaviour, July 1977.**

Green et al. (1977) made a thorough study of the properties of mixtures of paving grade asphalt and GTR at concentrations of about 25% by weight, which is particularly suited to reflective crack prevention. The work was carried out on behalf of the Arizona Department of Transportation. They describe the mixing process and examine the effect of rubber swelling in asphalt, proposing a mechanism by which the swelling occurs, and evaluating the effect of variables which influence this process including temperature, rubber particle size, rubber type, and the compatibility of the rubber and asphalt.

The swelling of specially formulated rubber samples in different oils was measured to develop the understanding of this mechanism and to design tests to assess the potential of different bitumens to cause swelling of tyre rubber. In cases where tests show that a particular bitumen does not cause sufficient swelling of the rubber, they suggest that modification of the asphalt with extender oils may achieve the desired result.

They also reviewed the effect of processing variables on the properties of the final asphalt-rubber mixture and identified several topics useful for quality control of the material. Test methods for monitoring the product quality were developed, particularly for monitoring the viscosity of asphalt-rubber binder at 60°C and also at ambient temperatures. Measurement of the elastic rebound of samples is suggested as a means of determining whether the asphalt-rubber mixture has properly reacted.

Their work identified a particular recipe which gave desirable viscoelastic properties. This recipe comprises:

> ..... *an AR 1000 paving grade asphalt containing 25% by weight of #16-#25 mesh gradation SBR rubber from reclaimed tires. The mixture was digested by stirring for 60 minutes at 190 °C (375 °F) before testing or dilution with kerosene. Asphalt rubber sources other than those used ..... may require a modification in the time-temperature-concentration parameters to achieve similar characteristics .....*

McDonald, C.H. 1971. An elastomer solution for alligator cracking in asphalt pavements. *Proceedings of the International Symposium on the Use of Rubber in Asphalt Pavements*, Salt Lake City, Utah, May 1971. Sponsored by the Utah Department of Highways (E. Lowell and B. Rufener, Eds): 363-375.

McDonald (1971) presents an early account of the use of GTR in asphalt pavements. This use arose from a desire to address the problem of fatigue cracking of pavements, particularly those subject to low temperatures when conventional pavements have low flexibility. Some discussion of the blending mechanism is given, followed by details of the first large scale application of asphalt-rubber pavement at Phoenix International Sky Harbour Airport, and of the use of diluents to temporarily control viscosity.

The use of pre-formed patches is described. These patches consist of sections of asphalt-rubber that have been reacted at high temperature, then cooled, and either rolled or cut into sections that may be tacked to a pavement surface using a tack coat or by applying heat. The patches had been applied to spalled or broken concrete, steel bridge decks, and in test sections on mountain roads at over 7000 ft (2100 m) elevation.

Experiments with an application directly onto a subgrade covered with a bituminous prime coat had shown promise, as had experiments with relatively impervious asphalt-rubber used to prevent bleeding of underlying asphalt layers and to restore skid resistance.

APPENDIX 2

REVIEWS OF LITERATURE ON "DRY" PROCESS RUBBER-MODIFIED ASPHALTIC CONCRETE

REVIEWS OF LITERATURE ON "DRY" PROCESS RUBBER-MODIFIED ASPHALTIC CONCRETE

A2.1 Introduction

The results of research and field trials using "dry" process bitumen-rubber blends are summarised below in chronological order of publication, from most recent to oldest.

A2.2 Reviews of Reports

Doty, R.N. 1988. Flexible pavement rehabilitation using asphalt-rubber contaminations: progress reports. *Transportation Research Record 1196*: 212-223.

Doty (1988) discusses construction and monitoring of sections of PlusRide pavement in comparison with conventional asphaltic concrete pavements and "wet" process asphalt-rubber pavements. From initial observations the performance of the PlusRide appears satisfactory, though some flushing and bleeding occurred on two of the three trial sections. A glaze on the surface of the pavements resulted in an initial low skid number, though this glaze effect disappeared after about six months.

McQuillen, J.L., Hossein, B.T., Hicks, R.G., Esch, D. 1988. Economic analysis of rubber modified asphalt mixes. *Journal of Transportation Engineering 114(3)*: 259-277.

McQuillen et al. (1988) report that, in the US, PlusRide pavements were first studied during the period 1979-1987 when 55 km of trial sections were laid by the Alaska Department of Transportation. Results of testing in Alaska show that an average field voids content of less than 5% is critical to attain to prevent ravelling. Consequently, higher than normal asphalt contents and greater compaction are required. Despite the high content of soft grade asphalt used in the trial section, no bleeding of the pavements has been recorded at temperatures up to 38°C.

The Alaskan research included laboratory evaluation of the effect of mix design on the properties of the final rubber-modified asphalt mix. Rubber gradation, rubber content and aggregate gradation were important in determining the asphalt content in the mix design, the fatigue life, and the modulus value of the mix. The results also showed that the fatigue life of the rubber-modified mixes is greater than that of the conventional asphalt. From the data, layer equivalencies could be calculated for conventional and rubber-modified pavements which enabled them to then estimate the cost effectiveness of the rubberised material.

La Force, R.F. 1987. Rubber modified asphalt concrete. ***Colorado Department of Highways, Report No. CDOH-SMB-R-87-15*** **(December 1987), 19pp.**

La Force (1987) describes the results of a study undertaken by the Colorado Department of Highways to evaluate PlusRide rubber-modified asphalt in the laboratory. The interest in the product arose particularly because the more flexible pavement had the ability to retard the formation of ice on the pavement, while also recognising its value of increased fatigue resistance, reduced thermal cracking and increased skid resistance. The tests were designed to determine the durability and moisture resistance of the PlusRide material using locally available asphalts and aggregates.

Results of the work showed that, when compacted with low void content, the PlusRide samples had good resistance to moisture damage. In assessing the material they found that laboratory techniques to measure stability and cohesion are not applicable to the flexible PlusRide mix.

In reviewing the performance of the four trial sections in the Colorado region, in each case cohesion failures of the pavement had occurred in the most trafficked areas. These failures were associated with base failures in only one of the four trial sections. Because of the higher cost of PlusRide and uncertainties in the application of existing design methods, the use of PlusRide pavements was not recommended at the time the report was prepared.

McQuillen, J.L., Hicks, R.G. 1987. Construction of rubber modified asphalt pavements. ***Journal of Construction Engineering and Management 113(4):*** **537-553.**

McQuillen and Hicks (1987) discuss practical aspects of the use of the PlusRide process by the Alaska Department of Highway Transportation and Public Facilities. They examine the production of the gap-graded aggregate, mix production, laying and compaction. By means of a questionnaire to contractors they also attempted to evaluate construction practices. Comments indicated that in almost all cases some difficulties with the material were experienced, including stickiness during transport and laying, with almost every respondent commenting on the material sticking to the drums of rollers.

Although placement of the material was generally achieved with no more difficulty than conventional asphalt, the perception of a higher risk resulted in increased contractors' prices. Full width vibratory screens were necessary for satisfactory laying of the mix. Air quality was a more frequent problem when using drum-dryer mix plant rather than batch plant. Low volumes of production were also a factor in making the production of the PlusRide mix costly.

Esch, D.C. 1982. Construction and benefits of rubber-modified asphalt pavements. *Transportation Research Record 860*: 5-13.

Esch (1982) discusses mix design and construction practices for PlusRide asphalt related to experience of the Alaska Department of Transportation and Public Facilities. Aggregate and rubber proportions and asphalt content were all studied, and their effects on fatigue life evaluated. Because very close control of the rubber content is necessary, batch plants are preferred for mixing although both continuous mix and drum-dryer mix plants have been successfully used. Compaction to the highest possible density with minimal voids (less than 5%) is essential to obtain good pavement performance. Although the mixes appear to have excessively high asphalt content, bleeding is not a problem.

Close conformance to all specifications was found crucial to ensure good pavement performance. The objective of retarding ice formation and increasing the skid resistance of the trial sections was readily achievable.

George, J.D., Piggott, M.R., Woodhams, R.T. 1978. *Recycling of scrap tires to improve pavement asphalts.* University of Toronto, Toronto, Ontario, Canada, May 15 1978.

George et al. (1978) present results of laboratory and field testing carried out by the University of Toronto, Canada. While a considerable amount of work was carried out, the analysis of the data, especially in terms of cost effectiveness, was less detailed than in some later studies.

APPENDIX 3

COST STUDIES OF BITUMEN-RUBBER PAVEMENTS

COST STUDIES OF BITUMEN-RUBBER PAVEMENTS

A3.1 Introduction

Reports of research and field trials which included cost studies of using bitumen-rubber or asphaltic concrete-rubber blends for pavements are summarised below in chronological order of publication, from most recent to oldest. Costs quoted from a report are in the currency of the country of origin at the time of the report's publication.

A3.2 Reviews of Reports

Charania, E., Cano, J.O., Schnormeier, R.H. 1991a. Twenty year study of asphalt rubber pavements in Phoenix, Arizona. ***Transportation Research Record 1307*****: 29-38.**

Charania, E., Cano, J.O., Schnormeier, R.H. 1991b. Rubberised asphalt - still sound after 20 years. ***Better Roads*****, August 1991, 35pp.**

Charania et al. (1991a, b) remark that the cost of asphalt-rubber chipseals applied in Phoenix, Arizona, is approximately twice that of a conventional chipseal. Early work in 1971 was initially about three times this cost. The same figures were quoted by Schnormeier (1980) suggesting either that costs have remained static in the period 1980 to 1991 or else the costing exercise has not been updated.

Takallou, M.B., Takallou, H.B. 1991. Benefits of recycling waste tires in rubber asphalt paving. ***Transportation Research Record 1310:*** **87-.**

Takallou and Takallou (1991) make a comparison of costs for both "wet" and "dry" process rubber-modified pavements and for conventional asphaltic concrete. Pavements constructed using the ARCO process, the patented PlusRide process, and the non-patented "generic" process, are compared. However, the calculations do not make allowance for expected cost savings in the long term, related to reduced maintenance and increased pavement life using rubber-modified asphalt.

Costs additional to the cost of conventional asphalt arise from an increased use in binder (2.0-2.5% for PlusRide and 1.0-1.5% for the generic process), the cost of adjusting the conventional aggregate grading to allow space for the rubber particles, the cost of the rubber itself, and the cost of royalty fees for the PlusRide system.

The generic system differs from the PlusRide system in that the rubber gradation is designed to be compatible with a specific dense graded aggregate, without modification of the grading curve (as is required in the PlusRide system). Although the generic system is patented, it has no royalty payment for its use. Costs of the mixes containing GTR and conventional asphalt are compared in Table A3.1.

Table A3.1 Increased cost (US$1991) of mixes using GTR compared with conventional asphalt mix (reproduced from Takallou et al. 1991).

Mix	Increase in cost/ton beyond conventional asphalt-standard (control)		
	Asphalt-rubber binder (Arizona process)	**RUMAC* (PlusRide process)**	**RUMAC* (generic process)**
Asphalt binder		2.40	1.80
Asphalt-rubber binder	23.10		
Aggregate		3.00	
Contractor overhead	3.00	3.00	3.00
Royalty		4.50	
Rubber		7.20	7.20
Total increase per ton	26.10	20.10	12.00

* RUMAC = Rubber-modified asphaltic concrete

In addition, the authors have calculated costs on a project basis, expressed both as cost per mile and also as the additional cost per tyre used in the mixtures (Table A3.2).

Table A3.2 Project costs (US$1991) of asphalt mixes using GTR and of conventional asphalt mixes (reproduced from Takallou et al. 1991).

Item	Conventional asphalt (standard)	Asphalt-rubber binder (Arizona process)	RUMAC* (PlusRide process)	RUMAC* (generic process)
Cost/ton ($)	28.00	54.10	48.10	40.00
Tonnage required per mile, 36 ft wide, 3" thick (tons)	3564	35160	3326	3374
Cost/mile ($)	99,792	190,216	159,981	134,960
Number of tyres recycled /mile	-	5274	16,630	16,630
Difference in paving costs/ recycled tyre	-	$17.14	$3.62	$2.11

* RUMAC = Rubber-modified asphaltic concrete

From this basis they argue that the additional cost of the generic process of US$2.11 per tyre could be offset by a subsidy or an environmental tax of the same amount to make the process economically feasible. They calculated additional costs of US$3.62 per tyre for the PlusRide process and US$17.14 for the ARCO process (largely a result of the cost quoted for the asphalt-rubber binder).

The authors' economic analysis relates only to the initial production and placing of the pavements. It does not take into account either the decreased maintenance or the increased lifetime of the asphalt-rubber pavements. They also do not attempt to evaluate cost savings from the disposal of tyres in pavements instead of disposal by other processes such as landfilling.

Hoyt, D.M., Lytton, R.L., Roberts F.L. 1988. Performance prediction and cost effectiveness of asphalt-rubber concrete in airport pavements. *Transportation Research Record 1207*: 88-99.

Hoyt et al. (1988) have carried out a cost-effectiveness evaluation for asphalt-rubber concrete designed for airport runway paving. The analysis required them to make several assumptions concerning costs of maintenance and rehabilitation of the asphalt-rubber concrete that they studied. The analysis also relied on the predicted crack and rut formation derived from the computer package ILLIPAVE. Their finding was that asphaltic-rubber concrete is cost effective though this depends on the climatic zone in which the pavement lies, which influences the lifetime of both the conventional asphaltic concrete and also the asphaltic-rubber concrete.

Based on costs of US$100 per ton for asphaltic cement and US$370 per ton for asphalt-rubber binder containing 18% rubber with no cutback, and assuming a job using at least 1000 tons of binder, the in-place cost of the asphalt-rubber mix is about 50% more than a conventional mix. Details of the cost breakdowns of the materials are given and are reproduced in Tables A3.3, A3.4 and A3.5.

In three of the four climatic zones which covered the study areas, the bitumen-rubber pavements with low or medium (optimum) binder contents were found to be cost-effective. Conventional asphalt was slightly more cost-effective in the zone described as dry no-freeze with assumed temperatures of 55°F (13°C; winter), 75°F (24°C; spring), 95°F (35°C; summer) and 75°F (24°C; autumn).

Table A3.3 In-place unit cost (US$1988) per ton of material for asphaltic concrete and for asphaltic-rubber concrete (reproduced from Hoyt et al. 1988).

Component	Asphaltic cement binder		Asphalt-rubber cement binder					
			Low binder		Medium binder		High binder	
	$/ton	%	$/ton	%	$/ton	%	$/ton	%
Binder*	4.80	16.3	15.65	36.5	17.50	38.8	19.35	41.0
Aggregate	8.85	30.1	8.85	20.6	8.85	19.7	8.85	18.7
Energy costs	1.28	4.4	1.28	3.0	1.28	2.8	1.28	2.7
Mixing	3.51	11.9	3.51	8.2	3.51	7.8	3.51	7.4
Haul, laydown, compaction**	5.92	20.1	6.51	15.2	6.51	14.4	6.51	13.8
Miscellaneous	0.66	2.2	0.66	1.5	0.66	1.5	0.66	1.4
Markup (15%)	4.42	15.0	6.43	15.0	6.76	15.0	7.09	15.0
Total	29.44	100.0	42.89	100.0	45.07	100.0	47.25	100.0

* 4.8% - asphaltic cement binder; 4.23% - low asphaltic-rubber cement binder; 4.73% - medium asphaltic-rubber cement binder; 5.23% - high asphaltic-rubber cement binder.
Asphaltic cement at US$100 per ton, and asphaltic-rubber cement at US$370 per ton, at the batch plant.

** 10% added to cost for compaction of asphaltic-rubber concrete due to anticipated increase in compaction temperature and/or compactive effort over that required for asphaltic concrete.

Table A3.4 In-place costs (US$1988) for asphaltic concrete and asphaltic-rubber concrete (reproduced from Hoyt et al. 1988).

Mix	In-place costs			Tons per square yard (T/SY)	In-place costs per square yard ($/SY)
	% binder	Per ton ($/ton)	Density (lb/ft)		
Asphaltic concrete	4.80	29.44	151.2	0.851	25.04
Asphaltic-rubber concrete					
Low binder	4.23	42.89	144.8	0.815	34.93
Medium binder	4.73	45.07	145.3	0.817	36.84
High binder	5.23	47.25	144.9	0.815	38.51

Table A3.5 Equivalent uniform annual construction costs (US$1988) for asphaltic concrete (AC) and asphaltic-rubber concrete (ARC) (reproduced from Hoyt et al. 1988).

Material	Climatic zone (temperature °F)	0.5 inch rutting		0.7 inch rutting	
		Age (years)	Cost* per square yard per year	Age (years)	Cost* per square yard per year
AC	Wet - freeze	1	25.04	4	6.63
ARC - low		12	3.58	17	<u>2.76</u>
ARC - medium		13	<u>3.55</u>	17	2.91
ARC - high		12	3.95	17	3.04
AC	Dry - freeze	1	25.04	5	5.41
ARC - low		13	<u>3.36</u>	18	2.65
ARC - medium		13	3.55	18	2.80
ARC - high		12	3.95	17	3.04
AC	Wet - no freeze	1	25.04	1	25.04
ARC - low		9	4.52	13	3.36
ARC - medium		11	<u>4.04</u>	15	<u>3.19</u>
ARC - high		8	5.50	13	3.71
AC	Dry - no freeze	10	<u>2.97</u>	15	<u>2.17</u>
ARC - low		11	3.83	16	2.88
ARC - medium		12	3.77	16	3.04
ARC - high		11	4.23	15	3.33

* Most cost-effective choices in each climatic zone are underlined.

McQuillen, J.L., Hossein, B.T., Hicks, R.G., Esch, D. 1988. Economic analysis of rubber modified asphalt mixes. ***Journal of Transportation Engineering 114(3):*** **259-277.**

McQuillen et al. (1988) have thoroughly examined the comparative costs of conventional pavement with PlusRide pavement from the basis of both capital cost and expected life. The evaluation, which was carried out for the Alaska Department of Transportation and Public Facilities, showed that the use of GTR through the PlusRide system was cost effective in the example studied. The cost comparison included data from a trial project in Anchorage, Alaska (Table A3.6).

Table A3.6 Economic comparison (in US$1988) of asphaltic cement and rubber-modified binders, Anchorage (reproduced from McQuillen et al. 1988).

Component	Conventional asphaltic cement binder		PlusRide rubber-modified binder	
	Cost ($/ton)	Cost (%)	Cost ($/ton)	Cost (%)
Binder	12.00	30.8	15.73	28.3
Rubber	-	-	7.20	12.9
Aggregate	8.00	20.5	8.25	14.8
Energy costs	1.50	3.8	1.75	3.1
Mixing	7.00	17.9	7.25	13.0
Haul	2.25	5.8	2.25	4.0
Placement	4.25	10.9	4.35	7.8
Engineering services and royalties	-	-	4.50	8.1
Markup	4.00	10.3	4.40	7.9
Total	39.00	100.0	55.68	100.0

Notes: Costs are in US$/ton of mix.

- Costs are generally based on material for approximately 16,500 sq yd (13,635 m^2) placed at 1½in. (38 mm) depth, 15 miles (24.1 km) from the plant.
- Rubber costs include shipment from Seattle, Washington, to Anchorage, Alaska.
- Binder cost is based on 6.5% by weight of mix for the traditional asphaltic cement and 8.5% by weight of mix for the rubber-modified.
- The rubber was calculated to be 3% by weight of total mix.

Calculations of the lifetime costs of the pavements were based on the results of laboratory testing to determine pavement properties. By assuming that annual capital and maintenance costs for conventional and rubber-modified mixes are equal over both their lifetimes the authors found that, to be cost effective, the lifetime of the rubber-modified mix must be 20-23 years compared with an assumed 15 years for the conventional pavement. An alternative calculation, ignoring probable maintenance savings using rubber-modified asphalt, increases this estimate of the required lifetime to 25-26 years depending on a discount rate ranging from 3.5-4.5%.

The material properties of the rubber-modified asphalt, as determined in the laboratory testing, allow the thickness of a rubber-modified asphalt with properties equivalent to a conventional asphalt to be determined. The test results in this case showed that the thickness of the pavement could be reduced by a factor of 1.2–1.4 when using rubber-modified asphalt mixtures. A comparison of calculated costs per square yard with savings from reduced pavement thickness revealed that the rubber-modified asphalt would be cost-effective if the thickness reduction factor was greater than 1.2–1.3. Since the test results confirmed that thickness reduction was possible, they concluded that the use of their rubber-modified asphalt mixtures was cost effective.

The authors were aware of additional benefits from using rubber-modified mixes, such as reduced winter maintenance, improved skid resistance and noise reduction, but did not include these parameters in their cost comparison.

Doty, R.N. 1988. Flexible pavement rehabilitation using asphalt-rubber contaminations: progress reports. ***Transportation Research Record 1196*****: 212-223.**

Doty (1988) has reported on the design and performance of a variety of conventional dense graded asphaltic concrete sections (DGAC), and on both "wet" (ARCO) and "dry" (PlusRide) process surface treatments placed for trial purposes by the California Department of Transportation.

While monitoring showed that the service life of the pavements incorporating GTR was likely to be considerably greater than that of conventional pavement, cost effectiveness was not possible to determine as most of the pavements had not failed. For example, although the thin (0.15-0.20 inch) conventional pavements in two of their 13 test segments (no. 7 and 8) had failed, the bitumen-rubber pavement seals of comparable thickness had not and the life of these segments was yet to be determined.

A summary of cost information is shown in Table A3.7, giving an indication of the extent to which the various bitumen-rubber pavements must outperform the conventional dense graded asphaltic concrete overlays to be cost-effective.

Table A3.7 Estimated in-place cost (US$1988) of pavement overlays (reproduced from Doty 1988).

Segment number	Pavement Overlay Type	Cost $ (square yard)
1	0.25" of ARS DGAC over ARS-SAMI	10.41
2	0.15" of ARS DGAC over ARS-SAMI	6.88
3	0.15" of ARS DGAC	5.37
4	0.15" of PlusRide DGAC	6.32
5	0.15" of PlusRide DGAC over ARS-SAMI	7.83
6	0.25" of PlusRide DGAC over ARS-SAMI	12.00
7	0.15" of conventional DGAC control	3.04
8	0.20" of conventional DGAC control	4.03
9	0.30" of conventional DGAC control	6.02
10	0.50" of conventional DGAC control	9.99
11	Double SAM, ARS binder	2.60
12	Double SAM, Sahuaro binder	2.62
13	Single SAM, ARS binder	1.56

DGAC = Dense graded asphaltic concrete
SAM = Stress-absorbing membrane
ARS = ARC = Asphaltic-rubber concrete
SAMI = Stress-absorbing membrane interlayer

Singh, J., Athay, L.D. 1983. Technical, cost and institutional aspects of asphalt-rubber use as a paving material. ***Conservation and Recycling 6(1/2):*** **21-26.**

Singh and Athay (1983), in comparing costs of asphalt-rubber applications with conventional asphalt, consider that there are difficulties because the alternatives are not well defined, the lifetimes of the asphalt-rubber surfaces are not known, possibilities for reducing future maintenance are not quantified, and value of deferring capital expenditure for major reconstruction requires consideration.

The estimated initial cost of a SAM is 45% more than for a conventional chipseal, although they consider it is likely to be cheaper in the long run.

The initial costs of a SAMI are considered to be much lower than the alternatives and the lifetime of the pavement will also be increased (Table A3.8).

The effect of regulations in the US that limit federal funding to applications thicker than 0.75 inches, is claimed to discourage state authorities from using thin SAM surfaces which may not qualify for funding. Instead they are being encouraged to apply a more expensive SAMI plus overlay, for which their own expenses are less because a SAMI attracts federal funding. Brief discussion of environmental problems posed by waste tyres includes the opinion that government policies and incentives are the key to solving the disposal problem.

Table A3.8 Costs (US$1983) of pavement rehabilitation alternatives (reproduced from Singh and Athay 1983).

Rehabilitation alternatives	Costs ($ yd^{-1})
Conventional chipseal	0.86
Asphalt-rubber chipseal (SAM)	1.25
Asphalt-rubber interlayer (SAMI)	
With 1.5 inch overlay of asphaltic concrete	3.73
With 0.75 inch open grade friction course containing 7% asphalt and rubber binder	3.10
Conventional 4 inch asphaltic concrete	5.75

Interesting figures on the energy savings from using asphalt-rubber are given. Based on the replacement of 20-25% of the asphalt by rubber, Singh and Athay claim that savings of 20,000 to 90,000 Btu per sq. yard may be achieved with SAM applications and almost 120,000 Btu per sq. yard for SAMI applications. The detail of the calculations is not included in the report.

Esch, D.C. 1982. Construction and benefits of rubber-modified asphalt pavements. ***Transportation Research Record 860*****: 5-13.**

Esch (1982) has evaluated the cost of several trial sections of PlusRide pavement in Fairbanks, Alaska. Allowing for purchase, shipping and handling of the rubber, royalties, plant modifications, and additional costs in compaction, the calculated in-place cost of the PlusRide is estimated to be 50% above the cost of conventional asphalt pavement. This estimate does not make any allowance of the ongoing costs of maintenance, or costs saving that may arise from increased skid resistance. Skid resistance increases because ice formation is reduced.

Bethune, J.D. 1978. Use of rubber in bituminous surfacing. ***ARRB Proceedings 9(3):*** **157-181.**

Bethune (1978) comments briefly on the cost of bitumen-rubber binder seals used by the Victorian Country Roads Board in Australia. Comparative costs (in A$ as at 1978) of seals using various aggregate sizes are given in Table A3.9.

Table A3.9 Cost (A$1978) comparison of conventional and bitumen rubber seals (reproduced from Bethune 1978).

Aggregate size (mm)	Conventional reseal (¢ per m^2)	Asphalt-rubber reseal (¢ per m^2)	% increase
7	51	59	16
10	61	100	66
13	73	108	48

George, J.D., Piggott, M.R., Woodhams, R.T. 1978. ***Recycling of scrap tires to improve pavement asphalts.*** **University of Toronto, Toronto, Ontario, Canada, May 15 1978.**

George et al. (1978) argue the economics of using tyre rubber in asphalt in a less rigorous manner than the other authors considered in this Appendix 3 of this report, based on their experience with the use of various trial mixes in Toronto, Canada. Their conclusion, that the calculated increase in costs is 26%, is considerably lower than costs reported from other studies, though the reason for the difference in costs is not clear.