Innovative Infrastructure Solutions (2022) 7:123
https://doi.org/10.1007/s41062-021-00721-8

TECHNICAL PAPER

Crushed stone partially substituted with shredded-waste tyres of motorcycles for low-volume road base construction: a feasibility study in Sri Lanka

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Received: 6 October 2021 / Accepted: 27 November 2021 / Published online: 9 December 2021

Abstract

In road base construction, substituting conventional mineral aggregates partially with waste tyre is envisaged to reduce the consumption of natural aggregate and to provide a sustainable way to dispose of waste tyres. This study explored the feasibility of deploying unbound crushed stone and shredded waste tyre mix for road base construction for low traffic volume roads in Sri Lanka through standard laboratory tests. The results revealed that, with the increase in shredded waste tyre (size 0.6 to 6.3 mm) content up to 8%, impact and static force resistance of the mix improved, whereas compaction characteristics worsened. As per Sri Lankan standards for pavement design, to retain sufficient compaction characteristics, 2% waste tyre substitution was feasible. Cost analysis revealed that a reduction of almost 10% of the conventional construction cost resulted in 2% shredded waste tyre substitution, and subsequent increase in waste tyre content showed only 1.6% cost reduction. Considering strength and cost contexts, this study recommends crushed stone partially substituted with 2% shredded waste tyre by weight for low traffic volume roads in Sri Lanka. The proposed method yields monetary savings of 1.142 million SLR (5630 USD) per km.

Keywords Road base · Crushed stone · Waste tyre · Cost feasibility · Mechanical properties

Introduction

As per The Ministry of Transport, Sri Lanka, vehicle population in the country has crossed 8 million in 2019, thereby the generation of waste tyres has escalated in the recent years [1]. The amount of waste tyres produced (in tonnes) in the United States of America, Norway, Italy and Thailand are 2.86 million, 32,000, 400,000 and 320,000, respectively [2–5]. Similarly, in Sri Lanka, if each vehicle needs changing tyres in every three to four years, the lowest possible amount of waste tyres generated per annum will be approximately 40,000 tonnes from all vehicle types [5]. Waste tyres are non-biodegradable and bulky and are difficult to dispose of in small islands like Sri Lanka. Disposal of waste tyres not only consumes money but also burdens environment.

In general, waste tyres are disposed of through landfills, incineration and pyrolysis, each one having its own advantages and disadvantages [6]. Landfills are the easiest way to scrap wastes, but unsuitable as they require large space to dispose, as waste tyres can become the breeding grounds for insects in tropical climates like Sri Lanka and as waste tyres may be prone to substantial fire risk due to high energy content [6]. To overcome pertaining issues in landfills, waste tyres could be incinerated; however, it releases harmful gases such as SO_2, H_2S, HCl and HCN to the air [4], and thus strongly discouraged by environmentalists. Pyrolysis, a relatively better option among these to dispose of waste tyres, is an endothermic process where waste tyre is decomposed chemically in an oxygen-free environment at elevated temperatures to produce pyro-oil [4, 6]. Though pyrolysis produces less amount of toxic gases, the applications of it are limited worldwide [4]. In order to enable deploying waste tyres in a greater variety of applications, Central Environmental Authority (CEA) of Sri Lanka has classified waste tyres into three categories and defined respective applications: partly worn tyres, retreaded tyres and end-of-life tyres [6]. Accordingly, CEA recommends the usage of end-of-life

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tyres in civil engineering applications such as construction, coastal protection, irrigation and habitat for sea life [6].

In a variety of civil engineering applications, deploying waste materials such as construction and demolition waste, tyre, coffee waste, plastic, ceramic, recycled olive core as partial replacements for coarse aggregates, fine particles and cementitious material, have gained considerable attention in the recent past [7–13]. Noticeably, waste tyres have been reportedly deployed in various construction projects due to their abundant quantity, economic affordability and complex-free processing [5, 14–16]. Using waste tyres as partial substitute for conventional construction materials not only helps to overcome material scarcity but also contributes to reduce environmental impact due to overexploitation of natural mineral deposits. In Sri Lanka, heightened law enforcement by authorities to prevent extraction of natural deposits has led to inadequate supply of mineral aggregates for road construction projects [17, 18]. Mineral aggregate is a vital material used in road construction that typically accounts for more than 90% by weight of the asphalt mixes [19]. Using waste tyres appropriately in place of natural mineral aggregate for road construction is envisaged to be a viable solution that has been already practiced in some parts of the globe, however, remains unexplored in Sri Lankan context [15, 16, 20]. From industry perspectives, the application of aggregate and waste tyre mix in road construction yields two benefits: one is promoting industry involvement in sustainable construction practices and second is paving innovative way for non-biodegradable waste disposal.

ASTM D6270 [21] stipulates guidelines for standard civil engineering applications of scraped tyres of the following forms: granulated rubber (below 425 µm to 12 mm), ground rubber (below 425 µm to 2 mm), powdered rubber (below 425 µm), rough shred (between 50 × 50 × 50 mm and 762 × 50 × 100 mm), tyre chips (12 to 50 mm) and tyre shreds (50 to 305 mm). Ground and powdered rubber are of large surface areas, which are preferred in bitumen modification, whereas granulated rubber is suitable for hot mix asphalt applications [2, 22]. The usage of tyre shreds and chips has been reported in embankment construction [2]. Xiao et al. [23] have showed that presence of crumb rubber improved Voids in Mineral Aggregate (VMA) in superpave mix design. Low-strength soil stabilized by cement and partially substituted with tyre chips has been recommended for low-cost and environmental friendly embankment construction in Thailand [5]. Signes et al. [15] have conducted a comprehensive study on replacing sub-ballast material with scrapped tyre and concluded that partial replacement up to 5% was feasible owing to bearing ability of the mix.

Heitzman [22] has indicated that deploying waste tyres in civil engineering applications was subjected to two major issues: One was defining standards for testing of the new technology and regulations pertaining to environment and the other one was adaptability of new technology by industries for large scale applications. Findings of the study by Eldin and Senouci [24] have highlighted that deploying waste tyre in road construction did not require significant additional effort, however, the compressibility issues due to the presence of rubber to be attended carefully. At initial stage, standard laboratory tests could be helpful to assess the application potential of mixes substituted with waste tyre in structural stability and cost contexts, which could be further extended or tuned to suit industrial applications [22, 25]. Researchers have conducted a series of laboratory experiments including density, flakiness index, water absorption, compaction, California Bearing Ratio (CBR), Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), Ten percent Fines Value (TFV), Los Angeles Abrasion Value (LAAV), cyclic load triaxial on conventional materials substituted with different types of wastes to obtain basic geotechnical, mechanical and thermal properties of alternative construction materials [26–31]. From environmental perspectives, non-biodegradable synthetic fiber in waste tyres is a major issue as long as its application is concerned. Petkovic et al. [3] proposed a framework to assess environmental impact from the use of recycled materials including shredded tyres in road construction in Norway. The proposed framework first characterized the given recycled material under specified conditions followed up by the corresponding risk assessment. A study by Sheehan et al. [32] showed that leachates collected from tyre shreds installed above the water table caused no adverse effects but saturated condition would result in highly localized toxic materials in water bodies. Another study by Eldin and Senouci [24] reported little or no influence from leachate formed from tyre shreds on groundwater.

Sri Lanka, a tropical island nation located in the Indian ocean, provides majority of the transport services through a well-connected road network, which comprises 12,500 km long national highways (15%) and provincial or local roads with low traffic volume (85%) [18, 33]. Since the major fraction of the roads is of low traffic volume, deploying cost-effective materials with sufficient structural stability for construction would immensely contribute in saving money. Using a new combination of materials in road construction is a complex process, which requires a comprehensive understanding of the behavior of the mixture and its compliance against design and construction standards. Current practices on pavement design and construction in Sri Lanka are governed by Sri Lankan Standards (SLS) for roads and Overseas Road Note 31 Standard (ORN 31), which are empirical and are based on parameters including subgrade strength (in terms of CBR) and traffic loading (in terms of axle loading) [34, 35]. This originated the presented study: crushed stone partially substituted with shredded waste tyres for the construction of low-volume road bases in Sri Lanka.

Research objective and scope

The presented work aimed to evaluate the feasibility of using unbound crushed stones partially substituted with shredded waste tyre in road bases. The objective of this study was to assess whether the mechanical properties of crushed stone and shredded waste tyre mixes fulfill the requirements for road bases established in SLS and ORN31 standards [34, 35]. Eventually, the waste tyre percentage that yielded satisfactory mechanical characteristics and with minimum total production cost was chosen. It should be understood that resilient modulus and permanent deformation are the most accurate and reliable parameters to evaluate the performance of unbound road bases [31, 36]. Currently, pavement design in Sri Lanka, however, follows empirical method based on CBR. This study, therefore, proposed a simple evaluation method to assess the performance of unbound crushed stone road base partially substituted with shredded waste tyre based on laboratory tests including compaction, CBR, AIV, TFV and LAAV.

The proposed assessment framework is complex-free and inexpensive to evaluate construction materials for road bases of low-volume roads. To the best of author's knowledge, using waste tyres for road bases remains unexplored in Sri Lankan context. The proposed technique has two major advantages: one is cost-effective solution to overcome material scarcity and the second is an alternative method to discard waste tyres.

Study framework

Figure 1 shows the detailed framework of this study. The study was conducted in three stages. At stage I, individual materials (crushed stone and shredded waste tyre) were characterized using standard laboratory tests to verify whether they were free from anomalies and were in compliance with standard requirements. Stage II consisted of standard laboratory tests on various compositions of crushed stone and shredded waste tyre mix to evaluate their resistance to compaction, impact, static and abrasion loadings. Also, the obtained parameters were checked against respective standard requirements. Production costs of alternative mix compositions were first computed in Stage III, and finally appropriate composition of crushed stone and shredded waste tyre mix with the lowest production cost that satisfied minimum strength requirements was chosen.

Materials and method

Material characterization

Dense graded crushed stone with particle size distribution shown in Fig. 2 was chosen for modification with waste tyre in this study. The selected composition was in accordance with standard requirement for aggregates with nominal maximum size of 20 mm for road bases as stipulated in ORN31 and SLS for roads [34, 35]. Crushed stone of different sizes as shown in Fig. 2a was first sieved separately and blended

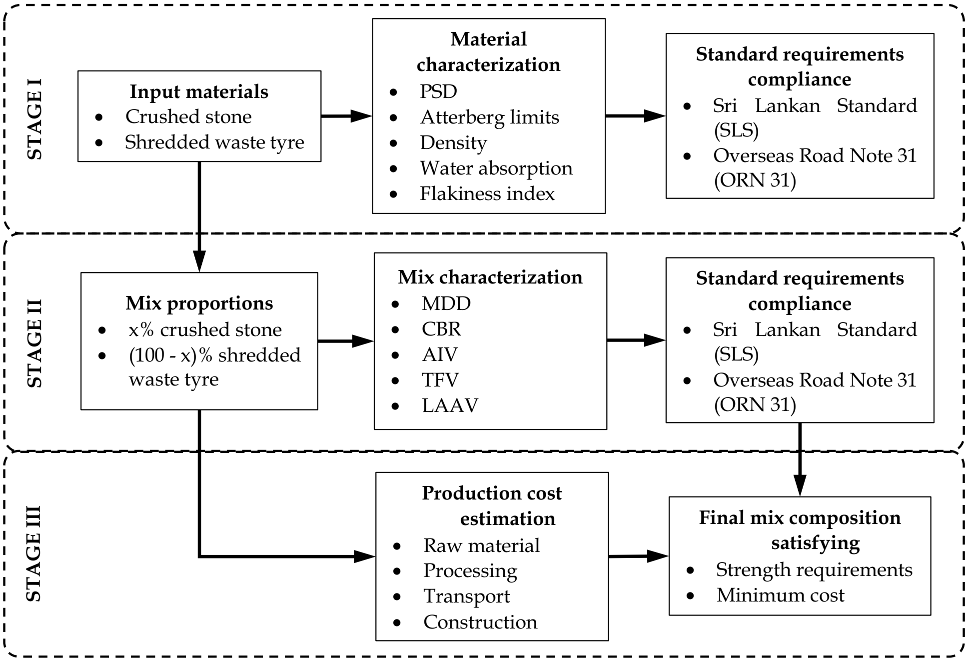
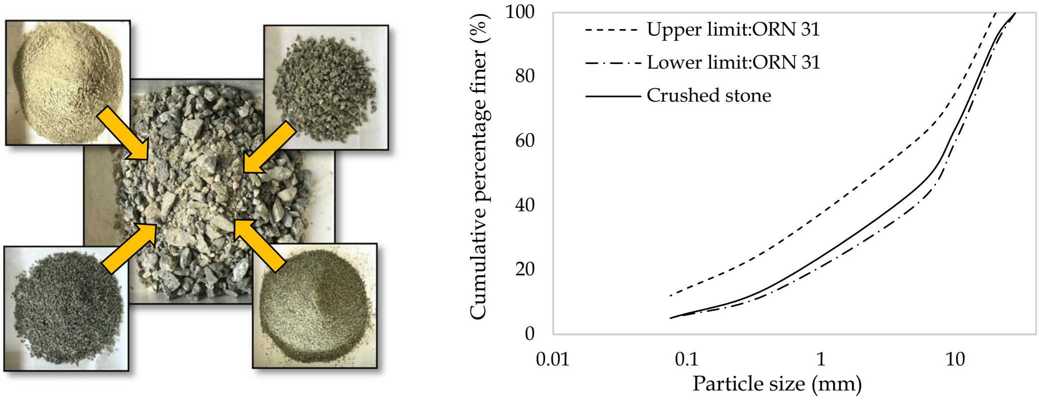
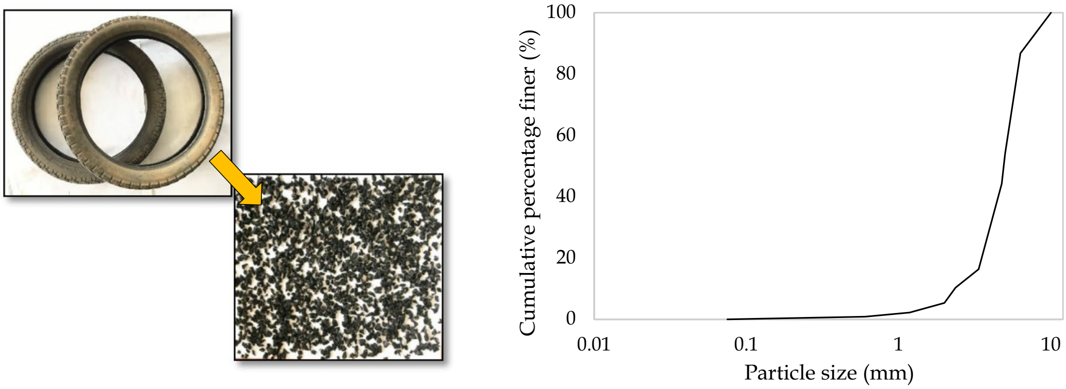


Fig. 1 Framework of the study



(a) Crushed stone **(b)** Particle size distribution of crushed stone



(c) Shredded motorcycle waste tyre **(d)** Particle size distribution of shredded motorcycle waste tyre

Fig. 2 Crushed stone and shredded motorcycle waste tyre deployed in the study

together in required proportions to obtain the required gradation (Fig. 2b).

Waste tyre chosen to be added to crushed stone was of motorcycle considering its local availability and simplicity in shredding. As per The Ministry of Transport, Sri Lanka, number of motorcycles in 2019 was 4.67 million, which was over 58% of the total number of vehicles [1]. Sri Lankan population commonly uses motorcycles for all kinds of commuting, which increases the chances of generating relatively higher share of motorcycle waste tyres. To capitalize on this, the study has been initiated with waste motorcycle tyres.

Waste tyre was first cleaned with water to remove impurities and dried in air. The steel belt reinforcement in the tyre was then removed manually with an angle grinder. After removing steel belt of 0.4 kg, the available amount of tyre for shredding was 2.4 kg, which was fed into shredder machine and sliced into crumbs. The shredder machine with power rating 15 kW, three phase, was operated for 40 s to produce tyre crumbs shown in Fig. 2c. Particle size distribution of crumbed waste tyre obtained from shredder machine is depicted in Fig. 2d. Grain size of prepared waste tyre crumb ranged from 0.6 to 6.3 mm, which belongs to the category of granulated rubber as per ASTM D6270 [21].

Initially, physical properties of crushed stone and shredded waste tyre were determined separately using standard laboratory tests [37–39], and are summarized in Table 1. The properties were found to be in compliance with respective standard requirements of materials used for road bases [34, 35], which implied that both crushed stone and shredded waste tyre had no specific influence on other mix parameters. Density and flakiness index lied in the typical range stipulated for aggregates in standards [34, 35]. Non-plastic nature of crushed stone ensured that its swell potential remains unaffected by moisture changes [34, 35]. Low water

Table 1 Properties of crushed stone and waste tyre

Material	Parameter	Value
Crushed stone	Uncompacted density (Mg/m^3)	1.720
	Flakiness index (%)	23.5
	Water absorption (%)	0.52
	Plasticity	Non-plastic
Waste tyre	Compacted density (Mg/m^3)	0.533
	Uncompacted density (Mg/m^3)	0.454

absorption was an indication that crushed stone had very low internal pores, thereby they were free from micro-fractures.

Mix characterization

Range of mix compositions of crushed stone with waste tyres for various engineering applications is found in contemporary literature. Speir and Witczak [40] used 0–15% granulated waste tyre/chips to substitute dense-graded aggregate base course/sand-sub-base. Promputthangkoon et al. [5] substituted cement-treated low-strength soil with 0–25% tyre chips. In another study, 3–10% ground rubber of 177 microns was used to partially substitute lateritic soil [41]. Signes et al. [15] replaced 1–10% aggregates with waste tyre for the application of sub-ballast layers in their study. Study by Gamalath et al. [42] showed that compressive strength of concrete paving blocks reduced drastically with the increase in rubber content in the mix. Understanding the fact that increasing waste tyre/rubber content reduces bearing ability of mix, this study selected waste tyre substitution by weight in the range of 0 to 8%. Accordingly, mixtures of alternative compositions of crushed stone and shredded waste tyre were prepared as shown in Table 2, to examine the influence of shredded waste tyre content in the mix.

The proposed mixes in Table 2 were subjected to series of laboratory tests according to BS and ASTM standards to examine density and strength characteristics of crushed stone–shredded waste tyre mix as follows: compressibility tests including modified Proctor compaction and CBR [43], Aggregate Impact Value (AIV) to examine the resistance to impact forces [44], Ten percent Fines Value (TFV) to examine the resistance to static forces [45] and Los Angeles Abrasion Value (LAAV) to assess the abrasion resistance [46].

Initially modified Proctor compaction was conducted on pure crushed stone (0% waste tyre) to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), which were 2.347 Mg/m^3 and 6.2%, respectively. Subsequent CBR tests with alternative waste tyre compositions were performed using the obtained MDD and OMC. AIV and TFV tests were conducted on 10–14 mm crushed stone sample by applying impact and static loadings stipulated in standards, respectively [44, 45]. LAAV test was performed on 9.5–19 mm crushed stone sample by exerting abrasive forces. Each test was carried out on at least 5 samples to minimize the effect of random error in the measurements. The CBR and strength-related parameters obtained from laboratory experiments were screened for outliers and then averaged out to find the mean of the concerned parameter. When the tests were repeated on samples, care was taken to maintain the same compaction configuration, load application, temperature and moisture between samples.

Cost estimation

Crushed stone used for road base construction in Sri Lanka is typically quarried from open-pit mines. The costs involved in laying road base with crushed stone are defined in Highway Schedule Rates (HSR), Sri Lanka [47], and are summarized in Table 3. Aggregate cost primarily includes extraction and crushing cost, loading and unloading cost, transport cost, and laying cost at construction site.

Similarly, cost involved in the preparation of shredded waste tyre, detailed in Table 4, includes cost of waste tyre, transport cost for collection and supply of waste tyre to construction site, shredding cost and labor cost. Generally, end-of-life tyres can be obtained free of charge from automobile shops, as they want to get rid of waste tyres as much as possible considering the hassle involved in discarding them. Transport cost, electricity cost, and labor cost were assigned in accordance with present industrial

Table 2 Crushed stone and shredded waste tyre mix proportions used in the experiments

	Mix ID					
	Mix-100	Mix-98	Mix-95	Mix-92		
Crushed stone (%)	100	98	95	92		
Shredded waste tyre (%)	00	02	05	08		
BS test sieve (mm)	Cumulative % passing				Upper limit: ORN 31	Lower limit: ORN 31
28	100	100	100	100	–	100
20	92	91	90	90	100	90
10	64	63	61	60	75	60
5	45	44	43	41	60	40
0.425	15	15	14	13	27	13
0.075	05	05	05	05	12	05

Table 3 The costs incurred in laying road bases with crushed stone

HSR code	Description of item	Measurement unit	Rate (SLR[a])
	Aggregate and rubble (ex-quarry—basic) including blasting, loading and piling (plant production)		
B0-308A	(19.0 mm) Aggregate	Per cu. m	2725.70
B0-309	(12.5 mm) Aggregate	Per cu. m	2593.70
B0-312	Crusher fines (6.3 mm downwards)	Per cu. m	1541.57
T1-007A	Transporting of material excluding loading (for distance more than 10 km)	Per cu. m/km	26.20
E1-022	Loading available soil	Per cu. m	181.25
M1-012A	Dense graded aggregate base spreading watering and compacting graded 37.5 mm aggregate to form a dense aggregate base using machinery including motor grader & roller hire charges (loose volume) [SSCM 405.1][34]	Per cu. m	2639.15
	[a]for the rate on compacted volume, increase the loose volume rate by 42%. If measurement is on end product, piling cost of aggregate as per A1-018 shall be deducted		
E1-021	Piling of available soil	Per cu. m	137.30

[a] 1 SLR = 0.005 USD

Table 4 The costs incurred in preparing shredded waste tyre

Description of item	Measurement unit	Rate (SLR[a])
Waste tyre cost	Per kg	0.00
Transport cost for waste tyre collection and supply to the site	Per cu. m/km	20.00
Power consumption [48]	Per kg	11.00
Machine depreciation	Per kg	1.00
Labor (includes loading, unloading, shredding and mixing)	Per kg	5.00

[a] 1 SLR = 0.005 USD

rates [47, 48]. Due to the absence of precise data, the machine depreciation cost was assumed to be 1 SLR/kg of shredded waste tyre production.

In this study, a road construction site located at 150 km from a quarry in the Northern part of Sri Lanka was considered for cost estimation of road base construction with the proposed mixture of crushed stone and shredded waste tyre. CBR values of subgrade in the construction site ranged between 15 and 20, and hence subgrade was assigned to strength class S5 as per ORN 31 [35]. Anticipating low traffic volume on the selected road, traffic class T3 was chosen for the analysis. For this road, according to ORN 31 [35], minimum required thicknesses of layers for granular road base/surface dressing pavement category were determined, and are shown in Fig. 3. As per Road Development Authority (RDA) regulations, typical width for roads with low traffic volume is 5.5 m [49]. All cost estimations were made considering 1 km long stretch of the road. For the given dimensions, the compacted volume of road base made of pure crushed stone was 962.50 cu. m (175 mm × 5.5 m × 1 km), which was considered for the replacement with alternative compositions of crushed stone and shredded waste tyre.

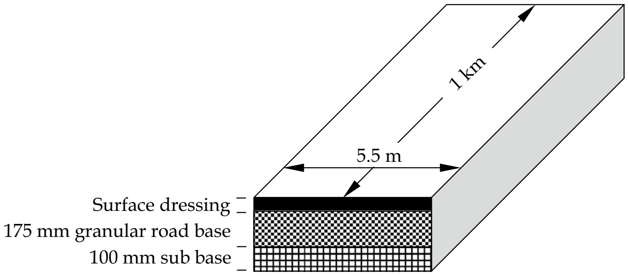


Fig. 3 Sectional details of the granular road base type pavement for subgrade strength class S5 and traffic class T3 (not to scale)

Results and discussion

Structural feasibility

The density- and strength-related parameters of alternative mix compositions obtained from laboratory tests are detailed along with their respective minimum/maximum standard requirements in Table 5. As it can be seen from Table 5, the compaction characteristics of crushed stone and shredded waste tyre mix, such as MDD and CBR, worsened as shredded waste tyre substitution in the mix was increased. During compaction and CBR tests, waste tyres in the mix absorbed a portion of applied compaction energy and dissipated it due to their resilient nature without transferring it to crushed stone matrix effectively, which prevented crushed stone particles from being fully compacted and being packed closely. Loss of close packing of grains led to decrease in density, and hence reduction in CBR value. When waste tyre content

Table 5 Parameters of crushed stone and shredded waste tyre mix of different compositions

Parameter	% of shredded waste tyre				Standard requirement
	0	2	5	8	
Maximum dry density (Mg/m^3)	2.347	2.066	1.957	1.865	1.750[a]
California bearing ratio (%)	159	87	49	16	80[a]
Aggregate impact value (%)	22.0	21.7	18.8	18.1	30[a]
Ten percent fines value (kN)	114	122	129	133	110[b]
Los Angeles abrasion value (%)	28.0	28.7	28.6	27.4	50[c]

[a] Sri Lankan Standard (SLS) [34]

[b] Overseas Road Note 31 Standard (ORN 31) [35]

[c] American Association of State Highway and Transportation Officials Standard (AASHTO) [50]

was increased in the mix, amount of compaction energy absorbed by waste tyres also proportionally increased, which contributed to additional reduction in density. Similar trends in bulk density were observed in studies that replaced rubber in sand concrete and unbound mixes made of coarse aggregates [15, 27, 31]. Signes et al. [15] reported a drastic drop in CBR values with the increase in waste tyre content for sub-ballast layers.

On the other hand, AIV and TFV presented in Table 5 indicate that the resistance of the mix to impact and static forces improved substantially with the increase in waste tyre substitution up to 8%. Shredded waste tyre particles surrounded crushed stone and resisted a fraction of applied impact and static forces, which prevented crushed stone particles from being directly impacted. This contributed to improve AIV and TFV. Accumulation of waste tyre in the mix further contributed to this reduction in direct impact on crushed stones. Literature reported improvement in ACV with the rise in rubber content in demolition waste mixed with crumb rubber [31]. The abrasion characteristics (LAAV) remained unaffected for all mixes. It could be attributed to the smaller size of waste tyre crumb used, which might be inadequate to negate abrasive forces between crushed stone particles.

The results summarized in Table 5 indicate that MDD, AIV, TFV and LAAV of all mix compositions with waste tyre replacement from 0 to 8% fulfilled their respective requirements for road bases stipulated in SLS and ORN31 standards. From CBR perspectives, partial substitution of shredded waste tyre up to 2% by weight was feasible for the construction of road base for low traffic volume roads. Finding alternative ways to improve CBR values will permit further substitution of shredded waste tyre in the mix.

Cost feasibility

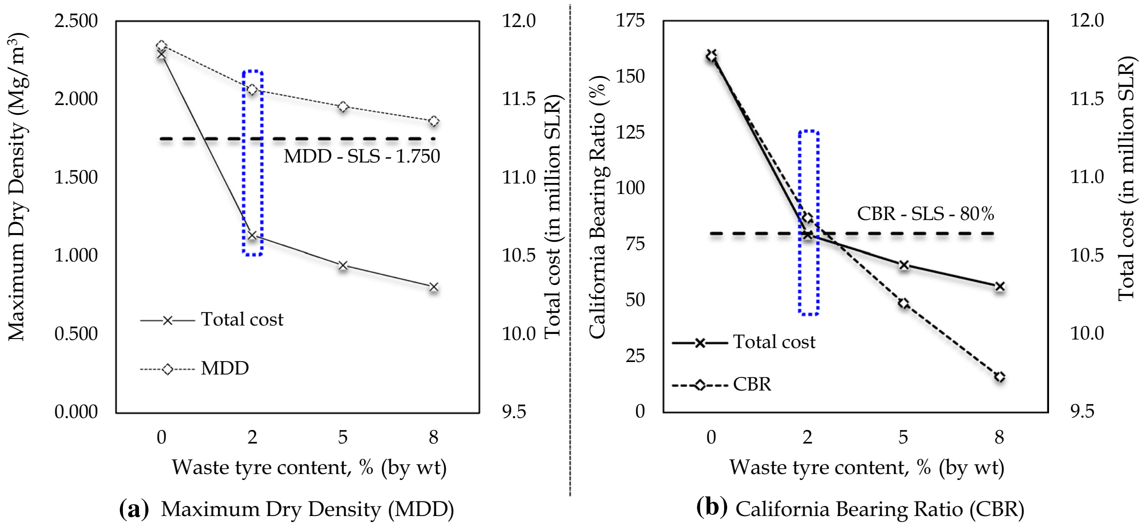
The estimated production cost of crushed stone and shredded waste tyre mix of various compositions for a predefined road base configuration (175 mm × 5.5 m × 1 km) is tabulated in Table 6. The total production cost consists of raw material cost, material processing cost, material transport cost and construction cost as defined in Tables 3 and 4. The results revealed that monetary savings increased when waste tyre substitution in the mix was increased from 2 to 8%. For 2% waste tyre substitution, 9.68% monetary savings from conventional construction cost was obtained. However, as the percentage of waste tyre substitution increased beyond 2%, only a marginal savings of 1.6% from conventional construction cost was observed in subsequent mixes. This could be attributed to the compromising effect between the reduction in crushed stone cost and increase in processing cost of shredded waste tyre. In overall, waste tyre substitution of 2–8% yielded monetary savings between 9.68 and 12.16%. It is worth mentioning that the proposed method is economically advantageous.

Figures 4 and 5 simultaneously compare the variations in density and strength parameters, and total production cost of mix against shredded waste tyre content in the mix. The

Table 6 Total cost incurred in preparing crushed stone and shredded waste tyre mix for road base

Description of item	Unit	% of shredded waste tyre			
		0	2	5	8
Required volume of crushed stone (includes 5% wastage)	cu. m	1379.03	1189.65	1092.39	1008.16
Required volume of shredded waste tyre (includes 5% wastage)	cu. m	–	75.51	178.82	272.67
Cost of crushed stone (in million)	SLR[a]	11.791	10.167	9.339	8.621
Cost of shredded waste tyre (in million)	SLR[a]	–	0.482	1.138	1.736
Total cost of crushed stone and shredded waste tyre mix (in million)	SLR[a]	11.791	10.649	10.477	10.357
Savings (in million)	SLR[a]	–	1.142	1.314	1.434
Percentage savings	%	–	9.68%	11.14%	12.16%

[a] 1 SLR = 0.005 USD



(a) Maximum Dry Density (MDD) **(b)** California Bearing Ratio (CBR)

Fig. 4 Variation of compaction characteristics of crushed stone partially substituted with various shredded waste tyre compositions

minimum/maximum requirement of each parameter according to standard, also is denoted in Figs. 4 and 5 to facilitate the selection of each attribute. As pointed out earlier, density-related parameters worsened; however, strength parameters improved with the accumulation of waste tyre in the mix. It is worth adding that, the change (increase or decrease) in density and strength parameters were gradual. This gradual change could be attributed to proportionately developed cushion effect in the mix with the accumulation of waste tyre particles, which contributed to partially cease load applications on crushed stone matrix. Total production cost of mix reduced with the increase in waste tyre content, noticeably exhibiting a drastic change between 0 and 2%.

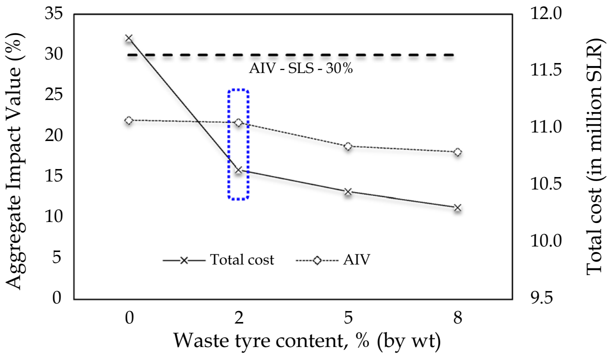
The comparison presented in Figs. 4 and 5 revealed that up to 2% shredded waste tyre substitution by weight was feasible, satisfying minimum/maximum density and strength requirements stipulated in SLS and ORN31 standards [34, 35]. Feasible waste tyre content corresponding to density and strength parameters, and total production cost, is denoted in Figs. 4 and 5. For all mix compositions, a considerable margin between laboratory test results and respective maximum standard requirements was observed for AIV, TFV and LAAV (Fig. 5). This emphasizes the fact that proposed method has potential to be extended to weak aggregate types with low impact, static and abrasive resistance to exploit the currently available margin. This extended work, however, is to be assessed for compaction behavior of mix before concluding about its application potential.

Conclusions

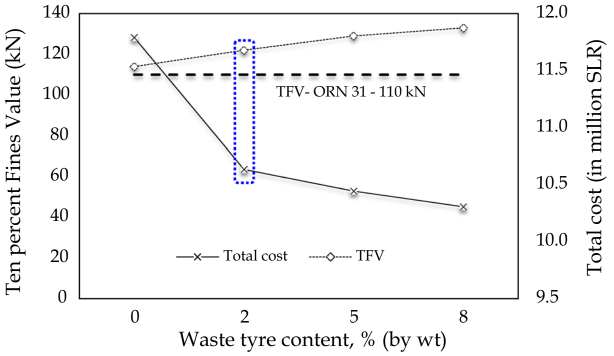
The application of waste material in road construction in Sri Lanka, a tropical weathered, developing nation with almost 85% low traffic volume roads, remains primitive to date. This study explored the feasibility of substituting unbound crushed stone with shredded waste tyre for road base construction in Sri Lanka and proposed a cost-effective solution through an experimental study stipulated in Overseas Road Note 31 (ORN31) and Sri Lankan Standards (SLS) for roads.

The salient conclusions drawn from the study are listed below:

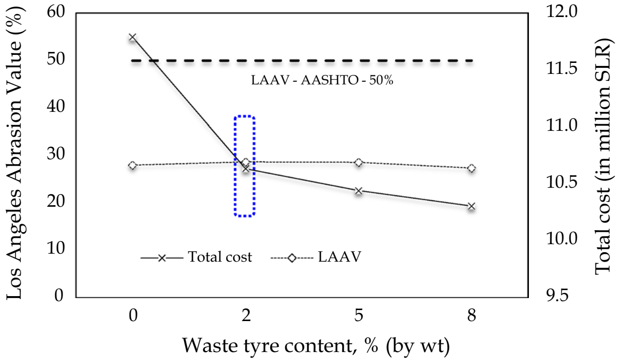
- The laboratory experiments performed in this study revealed that shredded waste tyre of size ranging from 0.6 to 6.3 mm has the potential to replace conventional crushed stone partially for road base construction.
- Study results confirmed that, with the accumulation of shredded waste tyre substitution up to 8%, resistance of the mix against impact and static force increased, whereas the compaction characteristics deteriorated.
- The estimated total cost of road base construction with crushed stone and shredded waste tyre mix showed a decreasing trend with the increase in shredded waste tyre substitution.
- The total cost reduction for the mixes substituted with shredded waste tyre from 0 to 2% by weight was 9.68%



(a) Aggregate Impact Value (AIV)



(b) Ten percent Fines Value (TFV)



(c) Los Angeles Abrasion Value (LAAV)

Fig. 5 Variation of impact (AIV), static (TFV) and abrasive (LAAV) force resistance of crushed stone partially substituted with various shredded waste tyre compositions

of the conventional road construction cost. Thereafter, a marginal cost reduction was observed due to increase in processing cost incurred in shredding of waste tyres.

- To be in par with the requirements stipulated in SLS and ORN31 standards, eventually, the waste tyre substitution up to 2% by weight was feasible for road base construction uncompromising required compaction characteristics.
- For 2% shredded waste substitution in the proposed mix, monetary savings of 1.142 million SLR (5630 USD) per km was obtained.

Recommendations and limitations

This research primarily focused on road base construction for low traffic volume roads in Sri Lanka. The proposed method contains two key aspects: a cost-effective material combination for local road construction industry, and a technique to dispose of non-biodegradable waste tyres. Findings of the study could be useful for developing nations with similar design practices, which suffer from budget constraints for road infrastructure development.

Considering density, strength and cost contexts, this study recommends crushed stone partially substituted with 2% shredded waste tyre by weight for road bases with low traffic volume (class T3 or below according to ORN31) in Sri Lanka. The possible monetary savings from this proposed method is 1.142 million SLR (5630 USD) per km.

The protocols and standards followed in this study are governed by Sri Lankan Standard (SLS) and Overseas Road Note 31 Standard (ORN 31), which are empirical and are based on parameters including subgrade strength (in terms of CBR) and traffic load (in terms of axle loading). It is noteworthy mentioning that current world practices emphasize the need of mechanistic design of pavements, which assess the performance of a pavement under repeated loading. Such design practices require comprehensive evaluation of additional parameters including resilient modulus and permanent deformation of pavements under repeated loading. Author of this paper, therefore, recommends that extension of this work to roads with heavy traffic volume or weak aggregate types require a thorough study on stress–strain relationship of the proposed material combination covering elastic and plastic deformations under repeated loading. By conducting cyclic triaxial tests, resilient modulus and permanent deformation could be accurately obtained.

Acknowledgements The authors acknowledge the Department of Civil Engineering, University of Jaffna, Sri Lanka for providing laboratory testing facilities.

Funding No funding obtained.

Availability of data and materials The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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