# Evaluating the Influence of Reclaimed Asphalt Shingles as Alternatives for Granular Base Course Materials

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## Abstract

Recycled asphalt shingles (RAS) constitute a widely generated material with significant potential to reduce construction costs and contribute to environmentally friendly practices by diverting waste from landfills, thereby promoting greener construction. Many researchers have underscored the importance of considering both negative and positive impacts of incorporating RAS into pavement structures. This approach offers sustainability, cost-effectiveness, and effective dust and noise control, coupled with low maintenance requirements when utilized in the surface layer of the pavement, as compared to the underlying disadvantages, including potential separation of RAS and aggregates, reduced cohesiveness, lower stability, and adverse effects on the ground and wildlife. This study provides a comprehensive literature review of research on the utilization of RAS material in road construction, along with laboratory evaluations assessing the use of RAS as a substitute for a proportion of base course material. Recycled asphalt shingles (RAS) were sourced from the City of Lethbridge and processed into particles smaller than 19 mm. The granular base course material was replaced with 10%, 20%, and 30% RAS, and the particle size distribution of the materials was analyzed to assess compatibility with the City of Lethbridge base course material specifications. The literature review indicates that RAS utilization in road construction is a sustainable method for using waste material with some negative impacts on performance which could be decreased using selected additives like clay, fly ash, etc. The results indicate a decrease in optimum moisture content (OMC) and maximum dry density (MDD) of the mixture with increased RAS content. A reduction in the strength of the materials prepared for the base course with increasing RAS is observed, and 10% RAS is determined to be the optimum content to maintain the 80% and higher California Bearing Ratio (CBR) value.

**Keywords**: Recycled asphalt shingles (RAS), Granular Base Course, Sustainability, Grain size distribution, CBR

## Introduction

Asphalt shingles are abundant and the most commonly used roofing material in North America, which makes them a suitable candidate for recycling. Recycling asphalt shingles leads to reduction of the volume of waste in landfills and can help cut down on the extraction of raw materials. It is speculated that the use of recycled asphalt shingles (RAS) in pavement structures is cheaper compared to virgin materials. However, to achieve a net positive financial impact, specific amounts of RAS must be mixed in with the aggregates. If used incorrectly, there is potential for the RAS material to weaken the granular base structure. To resolve this issue, multiple studies have been conducted by research teams from universities and governments across North America to investigate the properties of RAS. In this review, the components, processing, and application of RAS will be included, along with background related to cost and environmental concerns. The focus will be on the addition of RAS to granular materials in pavement structures. These include considerations related to the quantity and maximum size of RAS added or replaced with granular materials, the addition of RAS to materials with different grain size distributions and additives to RAS-granular mixtures.

The composition of RAS is about 25-35% asphalt cement, 60-70% aggregate, and 5-15% backing (paper/glass felt); however, the content can vary from one manufacturer to another. RAS can be included in aggregate mixtures for granular base courses as it stabilizes the materials well. Processed RAS can also be used in driveway and parking lot projects. The general steps involved in RAS processing are as follows: collection of tear-off asphalt shingles (TOAS) or manufacture waste asphalt shingles (MWAS), testing (of TOAS) for asbestos, sorting, grinding, screening, and storing. After processing, RAS can be used in construction projects. By using RAS, individuals overseeing construction projects can aid in reducing the excess of asphalt shingles (TOAS and MWAS) in landfills and reduce the construction footprint related to the use of raw materials. RAS can also be used to reduce the need for road maintenance to control dust, which is a benefit in terms of sustainability. However, potential adverse health effects should also be considered with the use of RAS, such as exposure to asbestos and polyaromatic hydrocarbons. Applications of RAS-aggregate mixtures as granular base layer in pavement structures, such as the use of RAS as a filler in base and subbase layers, have been considered successful, with proven stability. Based on the review, it was found that the use of RAS in larger aggregates results in issues with binding and the inclusion of RAS with smaller aggregates was found to be most effective. Materials with a high initial California bearing ratio (CBR) were also negatively impacted with the addition of RAS. The inclusion of additives such as fly ash lessened its compressibility. Overall, RAS-aggregate mixtures with lower RAS percentages are acceptable for granular base and subbase courses. The use of RAS-aggregate mixtures in the base and subbase for road construction has financial and environmental advantages as well as the potential to reduce dust, reduce road maintenance, and reduce road noise.

The main objectives of this research include:

- Literature review of research completed for RAS materials and its application in road construction.
- Investigating the possibility of using RAS for enhancing the properties of granular base materials.
- Determining the optimum RAS content for base course application.

The optimum RAS content will be selected to obtain the proper compaction and strength of the blend. The experimental laboratory work to determine the optimum RAS content includes sieve analysis, compaction, and CBR testing.

## Literature Review

Asphalt shingles, which are the most commonly used roofing material in North America, typically consist of asphalt cement, aggregate, and fibers[1, 2]. They are highly recyclable, containing five to six times more asphalt content than recycled asphalt pavement (RAP)[1, 3]. This recyclability, combined with the economic benefits of using recycled materials, has spurred interest in incorporating RAS into pavement construction[4]. Proper proportioning and matching with the correct material gradation are crucial for successful integration[5]. In 2002, the Grodinsky et al. endorsed a blend of RAS, RAP, and gravel for rural road construction, citing its superior quality and cost-effectiveness[6]. Hooper and Marr found that mixing RAS with certain plastic materials like clay improved strength, as demonstrated by the CBR test[7]. Both studies underscored the importance of eliminating debris such as nails and wood from RAS before use[6, 7].

### Material Components of RAS

Shingles are typically composed majority of asphalt cement and aggregate, and RAS aggregates from processed shingles have particle sizes within the #30 to #60 sieves (0.250 mm to 0.595 mm)[2, 8]. The asphalt cement used in shingles is stiffer than the asphalt cement used in asphalt mixes [3]. According to the American Society for Testing and Materials (ASTM), there are multiple kinds of asphalt roofing shingles[9]. Some are made with organic felt (ASTM D-225), and some are made with glass felt (ASTM D-3462)[9, 10, 11]. Newcomb et al.[9] describe shingles as being mostly composed of granular material. Table 1 outlines the components: ceramic granules (varying in color and made of granules with ceramic oxides), head lap granules (coal slag ground to the size of ceramic particles), back surface sand (sand added to prevent the shingles from sticking together in the package), and powdered limestone (asphalt stabilizer)[9]. Shingle components vary from manufacturer to manufacturer[9].

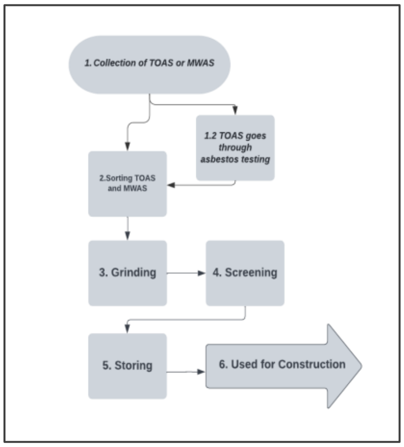
Table 1. Granular components of shingles[9]

| Component | Typical Quantity (Percent by weight of shingle) | Typical Size |
|---|---|---|
| Ceramic Granules | 10-20% | passing No. 12, retained No. 40 |
| Headlap Granule | 15-25% | passing No. 12, retained No. 40 |
| Backsurfer Sand | 5-10% | passing No. 40, retained No. 140 |
| Stabilizer | 15-30% | 90% passing No. 100, 70% passing No. 200 |

## Production of RAS

Figure 1 shows the processing of asphalt shingles for RAS, starting from when the shingles are torn off from a roof, or disposed of from a manufacturing plant (Step 1), as described in a report by Zhou et al.[12]. There are two types of RAS: tear off asphalt shingles (TOAS) and manufacturing waste asphalt shingles (MWAS). MWAS are preferred for use in hot asphalt mixes because there are less contaminants; however, TOAS are more abundant. To obtain contamination-free RAS from TOAS, either source separation must be done (i.e., separation of TOAS and non-shingle debris before hauling to the recycling facility) or mixed roofing material must be processed (i.e., no prior separation of TOAS and non-shingle debris). Next, the TOAS is evaluated for asbestos (Step 1.2). Some recycling plants have in-house asbestos testing capability, so that results can be received in a timely manner. After testing, both MWAS and TOAS are sorted manually to remove any debris, though less work is required for MWAS as there is little debris in the material (Step 2). Materials that must be removed from TOAS include cementitious shingles, shakes, transit siding (which contains asbestos), hazardous waste, plastic, paper, glass, metal, and other trash. Grinding is done after ensuring that the contains no debris (Step 3). Most of the material is ground to 13 mm, since this is the size of RAS most often used in asphalt paving; however, some material is ground to 20 mm for use as aggregate supplement. The material is then screened to ensure correct sizing and any oversize particles are removed (Step 4). The last step is to store the RAS until use (Step 5). When storing the RAS, it is imperative to cover the RAS stockpiles and separate TOAS-derived RAS from MWAS-derived RAS in the storage facility[12]. The market options for processed RAS have been summarized by Jameson et al.[5].

Figure 1. Flow chart for RAS production[12]



## Cost Considerations

The use of RAS as an alternative to virgin materials has been shown to cut the costs of projects. A survey by the National Asphalt Pavement Association (NAPA) in 2014 highlighted that the United States achieved a combined reduction of 2.8 billion United States dollars (USD) with the incorporation of RAS/RAP in roadway and construction projects[13]. Jameson reported a cost reduction (savings) of 3.50 USD per ton of hot mix asphalt (HMA) with RAS[5]. No direct calculations were reported for the financial feasibility of mixing RAS with granular base materials in the report, though cost information for the recycling process of RAS was outlined, which is a process that also includes shingle used for fillers[5]. A study by Williams et al.[14] represented the savings per ton achieved from replacing a portion of fine aggregate with RAS using the following formula:

$$\begin{aligned} &Savings\ from\ Fine\ aggregate \\ &\quad = New\ Fine\ Aggregate\ Cost\ \left(\frac{\$}{ton}\right) \times \%\ Fine\ Aggregate\ in\ RAS \\ &\quad \times \%\ RAS\ in\ Asphalt\ Mixture \end{aligned}$$

A study by Williams et al.[14] indicated savings of up to \$0.15 per ton based on the assumption that the cost of new fine aggregate is \$10/ton, the amount of fine aggregate in RAS is 30%, and the amount of RAS in the asphalt mixture is 5%. The savings from fine aggregates only account for a small amount of the overall savings achieved using RAS; however, with an increase in the price of new fine aggregate, the savings would also increase. While there are cost savings associated with using RAS rather than new materials, there are issues with the presence of asbestos in older shingles. Asbestos has been found in low amounts (an average of 0.8% in 368 samples) in old shingles; however, a study done in Benton County in 1997 still estimated savings of 10 USD per ton when using older shingles[6, 15].

## Environmental and Health Considerations related to Processing RAS and its Waste Material

Booz et al.[16] considered the environmental effects of asbestos content such as energy consumption, resource depletion, avoided landfill impact, and greenhouse gasses and concluded that, overall, there are definite environmental benefits to using recycled asphalt shingles.

### *Effects of RAS on Ground Water and Wildlife*

Assadollahi et al.[17] studied the effects of RAS used as fill material in soil (brown loess) on ground water in Shelby County, Tennessee. Monitoring changes in ground water is done to protect the plants and wildlife that could be affected by ground water pollution[17]. Ground water properties, including pH levels and chloride, phosphate, and iron content, showed no changes with the addition of RAS[17]. Alkalinity and hardness were affected slightly for lower RAS contents. Samples containing 100% RAS had 180 ppm of alkalinity, 600 ppm of CaCO3 hardness, resulted in an extremely high conductivity value, and showed significant impacts on turbidity[17].

### *Freeing up Landfill Space and Reducing Raw Material Use*

The disposal of asphalt shingles takes up space within landfills. In 1999, the United States alone was reported to have produced about 10 million tonnes of waste asphalt shingles annually annually[5]. In 2012, 1.25 million tonnes of asphalt shingle material were disposed in Canada[18]. A report by Booz et al.[16] indicates that use of 5% RAS in pavement material can avoid use of 0.23 yd3/ton by volume and 96 lbs/ton by mass. The following discussion relates to the inclusion of various materials (not necessarily RAS) in asphalt; however, many of the findings are applicable to the use of RAS. Booz et al.[16] also reasoned that since asphalt mixes contain bitumen, the use of recycled materials rather than virgin materials in binders can lessen the depletion of raw bitumen due to its use in asphalt binder.

### *Dust Control*

In RAS production, water is added to limit dust and keep the shingles cool while shredded[6]. The addition of water complies with environmental guidelines concerning dust generation[5]. In road use, RAS can be incorporated in granular base layers for dust control[19]. Processed RAS mixed with gravel decreased dust on roads (as determined by visual inspection) as well as lessening road noise and decreasing the need for future road maintenance[5, 15]. After one year of applying an RAS-aggregate mixture to rural roadways in Iowa, minimal dust was produced as a car drove at the speed of 80 km/h; furthermore, the road remained relatively dustless, by visual inspection, up to two years from treatment[15]. According to a research project by Wood et al.[20], adding processed RAS to gravel reduces wash boarding and controls dust on gravel roads and improves the performance of surface gravel. The fibers in processed RAS allow for better binding of granular material passing the 100 sieve (0.1 mm).

### *Asbestos*

Asbestos is the main environmental concern associated with the use of RAS[19]. It is known that exposure to asbestos on a regular basis led to the development of cancer[19, 21]. In 2000, 394 tons of shingles were collected from 95 different roof projects, with only shingles from one of the projects containing asbestos[6]. Before 1973, asbestos was present in roofing materials. However, as previously mentioned, the cost of testing older shingles for asbestos during the production of RAS is still cheaper than disposing of the shingle material altogether. Therefore, it is still beneficial to consider the use of old TOAS to produce RAS, despite the cost for testing for asbestos[15]. Many shingle processing companies also have in-house testing to ensure that proper regulations are being followed without slowing down the processing of RAS[12].

### *Polyaromatic Hydrocarbon*

The leaching of polyaromatic hydrocarbons (PAHs) into water is also a concern as these compounds can negatively affect human health[19]. Some PAHs are known to be carcinogenic, and long-term exposure of humans to PAHs can result in kidney and liver damage. Given these considerations, some states (including Maine) require permits for use of RAS[19].

## Performance of RAS/Aggregate Mixtures based on Granular Distribution and Characteristics, RAS Content, and Additives

This section includes discussion of the specifications of RAS-aggregate mixtures and the effect of inclusion of RAS on the performance of the granular material. Material performance is assessed based on attributes such as binding capability, compaction properties (Proctor test), resilient modulus, and CBR test results. The standard AASHTO-MP-23 relates to the use of RAS in asphalt mixtures and the required aggregate gradation for the RAS used.

A report by Anderson[22] indicates that at one site (Pownal site), RAS larger than 3/8 in (9.5 mm) maximum aggregate size was used, with 21% of the material retained on a 3/8 in (9.5 mm) screen. The RAS used at the Pownal site was not compliant with the applicable standards (AASHTO MP-23), and immediate deterioration was observed after construction[23]. At another site (Shaftsbury), which had a gradation closer to what was proposed (8% above the 3/8 in (9.5 mm) screen), and less issues were observed. The larger aggregates (about 25 mm in size) used at the Shaftsbury site prevented proper binding, and the 25 mm aggregates were observed to migrate to the surface. Once the larger particles were removed, however, less separation was observed between the paved aggregates. It should be noted that in a control sample that did not contain RAS, these issues were not observed.

MacEachern et al.[24] investigated the use of RAS as partial replacement for granular Class A material. Mixture designs of up to 30% RAS were studied, with aggregate/RAS mixtures of 90/10, 80/20, and 70/30 by weight. RAS with a maximum aggregate size of 4.75 mm was used in the mixtures. The particle size distribution was based on ASTM C136/C136M[25]. The optimum moisture content (OMC) was determined by a Proctor test following the method included in ASTM D698[26]. This OMC was then used when conducting CBR testing as in ASTM D1883[27]. The report shows as the RAS content increased; the strength of the mixture decreased by up to 85% compared to the use of virgin materials.

Shrestha et al.[28] studied two RAS materials of varied sizes: processed shingles and ground shingles. The processed shingles were TOAS free of debris such as nails, with particles passing 100% on a 4.75 mm sieve[28]. The ground shingles were processed shingles that were ground to a maximum size of 75 mm, with 40% passing a 4.75 mm sieve[28]. The shingles was mixed with five materials: quarried crushed limestone, natural gravel (with 72% crushed particles), and three types of recycled concrete aggregate (RCA), to determine which mixture gave the best performance when mixed with the shingles. Mixtures with three different aggregate gradations were assessed (RCA 1, 2 and 3). CBR was used to evaluate the strength of the aggregate-RCA mixtures at the OMC. The OMC was relatively unchanged with the addition of shingles. The comparisons for RCA 1 and RCA 2 with ground and processed shingles show that ground shingles had more stability compared to processed shingles. The result also shows that the mixture RCA 1, which has a higher OMC, was less stable than RCA 2. The addition of shingles to three types of RCA shows that for RCA 3, which initially has a high stability value, an increase in ground shingle content resulted in reduced stability[28]. Materials with a CBR of about 100% or less, such as RCA 1 and RCA 2, show an improvement of up to 5% with ground shingles added[28]. The addition of ground shingles to limestone (initial CBR of 140%) led to a decrease in stability, and the addition of up to 5% shingles to crushed gravel (initial CBR of 120%) resulted in a slight increase in stability. For fine-grained soils with a maximum particle size of 2.36 mm and 5% passing a 75 µm sieve, the mixtures containing 5% shingles showed increased stability, with the maximum stability observed for 10% RAS content. Shrestha et al. concluded that using up to 5% or 8% RAS, in some cases, can improve the stability of granular materials. However, for materials that already have a high CBR (above 100%), the addition of RAS decreased the performance, as indicated by CBR testing[28]. Despite RAS decreasing the CBR of materials with a high initial stability (RCA 2, RCA 3, limestone, and gravel), these mixtures were not considered to be unsuitable for subgrade paving use. However, it was noted that further investigation is needed for a comprehensive evaluation of inclusion of recycled shingles in granular materials.

Hooper and Marr[7], aimed to obtain baseline quantitative data of the mechanical and physical effects of shingles on soil. The shingles used in this study were pre-consumer, off-specification shingles that were ground and passed through a 76-mm screen, then ground further and passed a 25.4-mm screen. For this study, the RAS comprised the ground asphalt shingles that passed the 25.4-mm screen. RAS was added to crushed stone gravel (CSG), silty sand, clean sand, and clay with different percentages (23%, 33%, 50%, 67%, and 100% RAS by volume). Mixtures of RAS with stone gravel, silty sand, clean sand, and clay were found to be acceptable sub-grade support for pavement. The parameters used for this study can be found in ASTM C117/136 (for sieve analysis), ASTM D4318 (Atterberg limits), ASTM D1557/AASHTO T180 (Proctor test), and ASTM D188 (CBR test)[25, 29, 30, 31, 32, 33]. The authors concluded that for weak materials such as clay, the addition of shingles with particle sizes of 25.4 mm or less can improve the strength of the mixture, as the clay has cohesiveness. For stronger materials, such as gravel and sand, shingles can decrease the strength if the original material has a high CBR value. It is inferred that in gravels and sands, there is already interparticle friction between particles, so the addition of RAS lessens this effect, resulting in a weaker mixture.

Soleimanbeigi et al.[34] researched and evaluated the geotechnical properties of RAS to be used as backfill or filling material in highway embankments. The materials evaluated were RAS combined with either foundry slag (FS) (waste material from molten metal poured into a mould in metal foundries), or bottom ash (BA) (a coarser component of coal combustion waste that settles at the bottom of power plant boilers)[35, 36]. To determine the granular distribution, the procedures in ASTM D422 were followed. The results show that pure RAS is a compressible material for structural fill[38]. The engineering properties of RAS:FS was compared to a control mix of glacial outwash sand, which is a natural soil found in Wisconsin. The RAS:BA and RAS:FS mixtures were found to have a lower unit weight when dry, which makes them a preferred alternative to natural compacted soils. As well, the RAS:BA and RAS:FS mixtures provided good drainage capacity for use as structural fill, and mixtures of RAS of up to 50% with BA or FS were unaffected by confining pressure. The addition of BA or FS to the soil mixture reduced both short-term and long-term compression. The study concludes that mixtures of RAS and BA or RAS and FS are appropriate for use as structural fill. However, environmental implications were not addressed during the study, therefore further assessments must be done.

Warner et al.[39] studied RAS mixtures — including RAS, RAS stabilized with fly ash (S-RAS), RAS-aggregate mixtures, and RAS-silt mixtures — and evaluated each mixture based on particle size, compaction characteristics, CBR, unconfined compressive strength, and resilient modulus. The study was conducted to gain an understanding of the precise specification of RAS, understanding the effect of the inclusion of fly ash (FA) in RAS and implementation of RAS mixtures in aggregate base (AB) and aggregate subbase (ASB). Fly ash is a by-product of coal combustion and contains the inorganic and incombustible parts of the coal, it differs from bottom ash as it is lighter and does not settle at the bottom of power plant boilers[40, 36]. The RAS gradations studied were 51 mm, 25 mm, 19 mm, 10 mm, and 5 mm (referred to using the maximum particle size in each gradation). Larger RAS particles are angular and plate-like, whereas smaller RAS particles are rounded and smoother. The smoother particles (less than 10 mm) are better for binding than larger particles and have a higher compacted weight. Grade 2 gravel (a poorly graded gravel with silt and sand, as specified by the Wisconsin Department of Transportation (WisDOT)) was used as the representative base coarse aggregate[39]. Boardman silt (sandy silt, liquid limit: 22%, plasticity index: 1%) was used as the representative embankment fill soil[39]. The Grade 2 gravel and Broadman silt were mixed with RAS in a 50:50 ratio (by mass). The OMC of these mixtures ranged between 7 and 14% and the compaction was determined to be 95% of standard maximum dry unit weight. The CBR test was done on the mixtures using ASTM D1883 standards to assess the stability. Warner et al. conclude that unstabilized RAS can be used for fill material and as a subbase but should not be used for base materials, with reference to the test for resilient modulus[39]. The authors determined that RAS-aggregate mixtures can be used as a subbase material and sometimes as a base material, even when not stabilized[39]; noting that the mixture exhibits a decrease in resilient modulus as the RAS content of the mixture increases. RAS-Grade 2 granular backfill (with a 50:50 ratio by mass) gave a resilient modulus value of 77 MPa when the unstabilized mixture was tested and was found to be an acceptable material for subbase and base courses[39]. The stabilized RAS mixtures still showed a high susceptibility to penetrative deformation (though stabilized RAS mixtures are less susceptible to deformation compared to unstabilized mixtures) and were noted to be highly susceptible to penetrative deformation when unpaved (CBR < 10). Low plasticity clay was shown to have the most improvement in resilient modulus with stabilization, but stabilization of RAS-aggregate mixtures with FA showed only slight improvements. It is inferred that due to the high content of asphalt in RAS, the cementation activity lessens which decreases the binding ability[39].

## Strengths and Considerations of using RAS

### Assumptions Within the Studies

Warner et al.[39], and MacEachern et al.[24] assumed that RAS takes on similar material characteristics to granular materials such as soils and gravels used within their respective studies, since there were limited studies regarding the use of RAS. However, in the future, should there be more comprehensive standards for RAS in place, the newer standards should be followed[39]. At the time that Warner et al.,[39] conducted their study on the use of RAS, different aggregate plants (where waste shingles are processed) had different methods for procuring and processing the shingles. The literature suggests a standardization of RAS procurement and processing for uniformity.

### *Presence of Asbestos*

Multiple studies have addressed concerns related to the asbestos content in RAS[6, 9, 12, 5, 15, 16, 28, 39]. Though minimal amounts of asbestos exist in roofing materials at present, since it was phased out in the early 1980s, organizations for transportation (e.g.: Vermont Agency for Transportation) require that either RAS is tested or new asphalt shingles made without asbestos are used[6, 9, 5, 28].

### *Debris in RAS Material*

In most literature studies related to RAS, the importance of removing debris, specifically nails, from RAS was emphasized[6, 7, 12, 5, 16, 22, 28, 34, 39]. Removal of nails and other debris from material before paving can minimize the risk of wheel puncture. Marks et al.[15] reported the removal of 1/3 of a kilogram of nails from three hundred tons of waste shingles added to aggregates, later paved in Benton County, Iowa. Wood et al.[20] enforced a specification for RAS to have a maximum of 0.5% weight on a 4.75 mm sieve; the debris removed included nails.

### *Additives to Strengthen RAS Mixtures*

Study by MacEachern et al.[24] recommend further investigation regarding additives such as asphalt emulsions and fly ash to strengthen mixtures containing higher amounts of RAS. Warner et al.[39] investigated the use of additives and asphalt emulsions to increase the strength of RAS materials and found that materials with low plasticity were improved most by additives such as fly ash. Soleimanbeigi et al.[34] added foundry slag to combat the over-compressibility that is attributed to RAS material.

## Applications of RAS in Road Construction

### *Aggregates on Gravel Roads*

The inclusion of RAS in gravel roads was examined by the Vermont Agency of Transportation[22]. Typical construction practices were followed in the project at Pownal, with the additional step of roller compacting. First, the grader passed over the existing road, then an RAS-gravel mixture was dumped and spread using a tractor with a rake. After spreading, a solution of chloride was applied, then a two-ton roller passed over the road twice. A site in Shaftsbury was also done using a similar process (with ditch clearing conducted before construction). In Shaftsbury, compaction was done by passing the roadway twice with a 13.75-ton smooth vibratory roller (according to specifications). At Pownal, the road showed deterioration after construction, as the RAS-gravel aggregates used had particle size larger than targeted; however, this was improved once large aggregates (with a size of 25.4 mm or higher) were removed from the mixture. The site at Shaftsbury presented little to no issues. Overall, the RAS-gravel material performs well using the same installation methods.

Wood et al.[20] conducted a field test with a mixture of RAS (from TOAS) and Class 5 gravel in a 1:1 ratio in Jackson Country, Minnesota in October 2012[41]. Two road sections were considered, one with RAS and the other without. An inspection in June 2013 confirmed that there was less dust and wash boarding in the sections that included RAS compared to those without. During the spring thaw, roads containing RAS were more stable, based on visual inspections. Also, in October 2012, Class 6 limestone was used as surfacing gravel in one location, and a 1:1 mixture of surface gravel mixed with RAS (from TOAS) was used at another location (Goodhue County, Minnesota)[41]. In June 2013, the performance of the Class 6 limestone road was assessed: the two sections (with and without RAS) showed minor difference from each other, with both showing acceptable performance.

***Other Applications***

RAS is used as compacted road bases and subbases in gravel road construction, as well as for dust control in gravel roads. The use of RAS has also reported as a mineral supplement in cement kilns, and in cold patch for roads[34]. There are drawbacks with using RAS in these applications, as the properties and standard specifications are limited[34].

## Research methodology

The City of Lethbridge provided the RAS material and granular material specifications (typical base course material used in the City of Lethbridge). After receiving, the RAS was processed and crushed, and a sieve analysis was performed to investigate the particle size distribution of each material (Figure 2). Thereafter, blends were fabricated using different combinations of RAS and aggregates (10/90, 20/80, 30/70) in addition to the control sample, which contained no RAS.

Different laboratory testing procedures were done in this study to evaluate the strength and compaction of the samples, as summarized in Figure 3.

Figure 2. (a) Processed RAS and (b) Unprocessed RAS

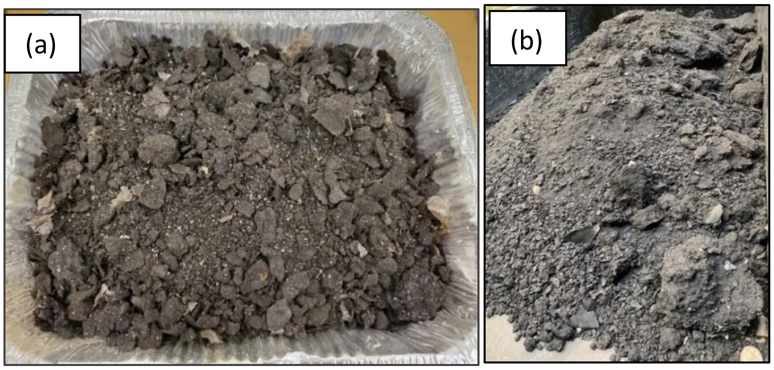
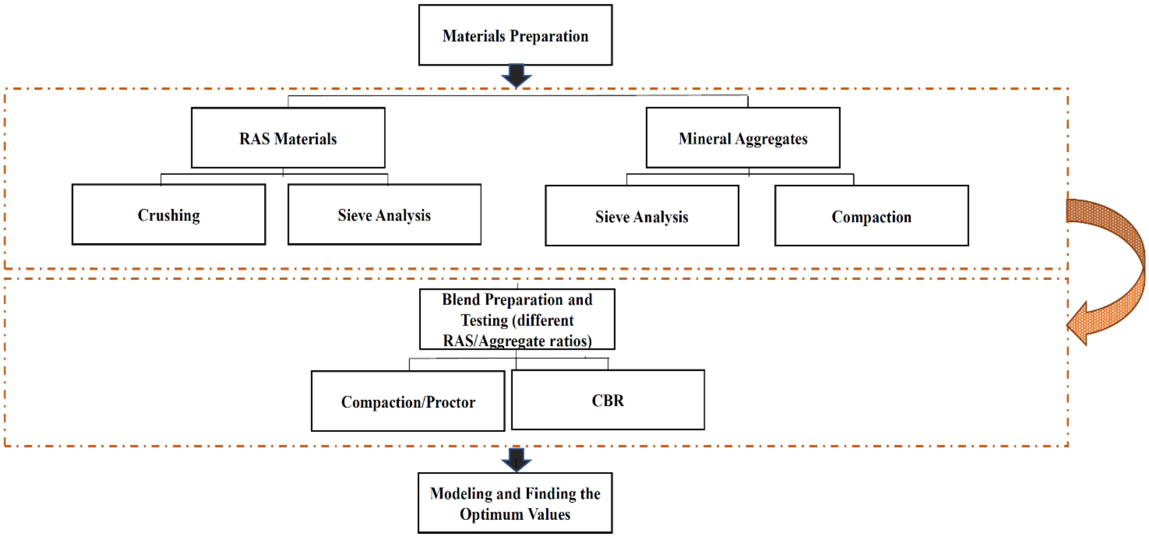


Figure 3. Methodology flow-chart



# Materials

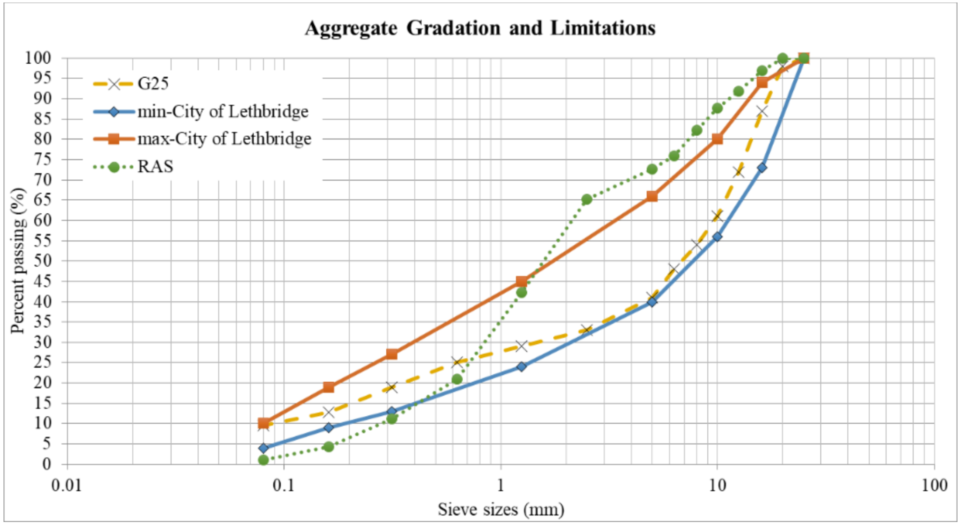
## Granular base material

Aggregates were collected from a local plant in Edmonton, and the properties of the materials were determined for the gradation provided by the City of Lethbridge, as shown in Table 2. Typical values for the specific gravity of the aggregates for granular base gravel provided by the City of Lethbridge are between 2.60 and 2.65. The Los Angles abrasion tests typically resulted in the 20% range. The aggregate gradation (G25) was within the gradation envelopes specified by the City of Lethbridge[42] (Figure 4).

Table 2. Properties of aggregates

| Property (unit) | | Standard | Results |
|---|---|---|---|
| Fine aggregates | Specific gravity ($G_{fa}$) | ASTM C128[42] | 2.645 |
| | Absorption of water (%) | | 0.523 |
| Coarse aggregates | Specific gravity ($G_{ca}$) | ASTM C127[43] | 2.654 |
| | Absorption of water (%) | | 0.784 |
| Abrasion of coarse aggregates (%) | | ASTM C131[44] | 23 |

Figure 4. Aggregate and RAS gradations and limits



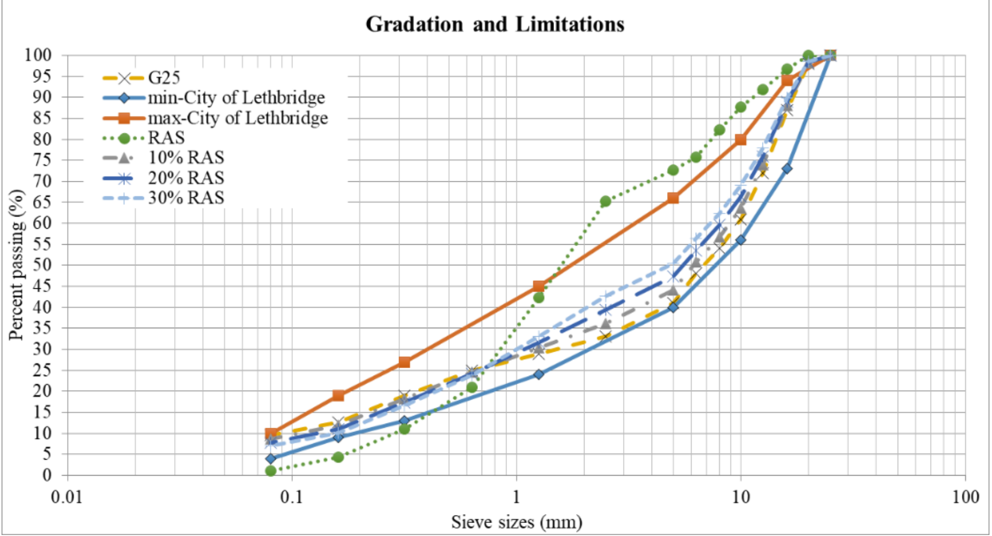
## Reclaimed asphalt shingles

Reclaimed asphalt shingles (RAS) were provided by the City of Lethbridge and processed to particles smaller than 19 mm. Sieve analysis was done on the processed RAS in the lab, and the results are presented in Table 3, as well as the gradation for the mixtures containing 10%, 20%, and 30% RAS with the limits of the gradations specified for a granular base layer. The aggregate gradation suggested by the City of Lethbridge, considering the replacement of some portion of the aggregate with RAS, was used to generate the new gradation. Increasing RAS content results in finer gradation of the mixtures. All the gradations investigated were within the gradation envelope provided by the City of Lethbridge[42]. The sample of RAS received at the University of Alberta is shown in Figure 5.

Table 3. Mixture gradations and limits

| Sieve size (mm) | Limit | RAS | 100% Aggregates | 10% RAS/90% Aggregates | 20% RAS/80% Aggregates | 30% RAS/70% Aggregates |
|---|---|---|---|---|---|---|
| 25 | 100 | 100 | 100.0 | 100.0 | 100.0 | 100.0 |
| 20 | - | 100 | 98.0 | 98.2 | 98.4 | 98.6 |
| 16 | 73-94 | 96.8 | 87.0 | 88.0 | 89.0 | 89.9 |
| 12.5 | - | 91.9 | 72.0 | 74.0 | 76.0 | 78.0 |
| 10 | 56-80 | 87.8 | 61.0 | 63.7 | 66.4 | 69.0 |
| 8.0 | - | 82.2 | 54.0 | 56.8 | 59.6 | 62.5 |
| 6.3 | - | 75.8 | 48.0 | 50.8 | 53.6 | 56.4 |
| 5.0 | 40-66 | 72.7 | 41.0 | 44.2 | 47.3 | 50.5 |
| 2.5 | - | 65.3 | 33.0 | 36.2 | 39.5 | 42.7 |
| 1.25 | 24-45 | 42.3 | 29.0 | 30.3 | 31.7 | 33.0 |
| 0.63 | - | 20.9 | 25.0 | 24.6 | 24.2 | 23.8 |
| 0.315 | 13-27 | 11.1 | 19.0 | 18.2 | 17.4 | 16.6 |
| 0.16 | 9-19 | 4.30 | 12.7 | 11.9 | 11.0 | 10.2 |
| 0.08 | 4-10 | 1.00 | 9.5 | 8.60 | 7.80 | 6.90 |

Figure 5. Modified gradation of the mixture after adding RAS and limits



## Test matrix and results

### Mix preparation process

Samples were prepared for the tests determined in the test matrix for both Proctor[33] and CBR[30] tests using different percentages of RAS and aggregates based on the information provided in Table 4. Aggregates were heated in an oven overnight (at 110 °C) to remove the moisture and cooled to room temperature before mixing with the amount of water required to obtain the OMC and compact. Processed RAS was used for the mixtures, and the gradation of the aggregates used to prepare the mix was based on the sieve analysis provided for the target gradation (G25). Figure 6 shows the mixing process.

Figure 6. (a) adding RAS to the aggregates and (b) mixed sample (20% RAS)

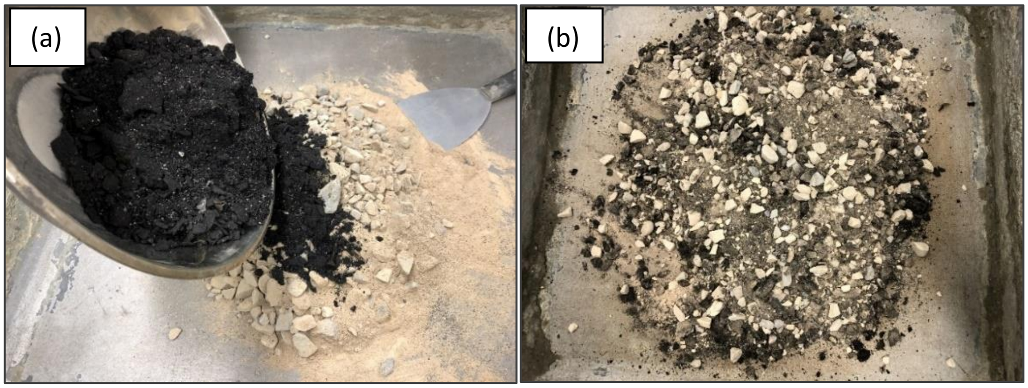


Table 4. Test matrix for the mixtures

| Sample ID | RAS content (%) | Aggregate content (%) |
|---|---|---|
| 0% RAS | 0 | 100 |
| 10% RAS | 10 | 90 |
| 20% RAS | 20 | 80 |
| 30% RAS | 30 | 70 |

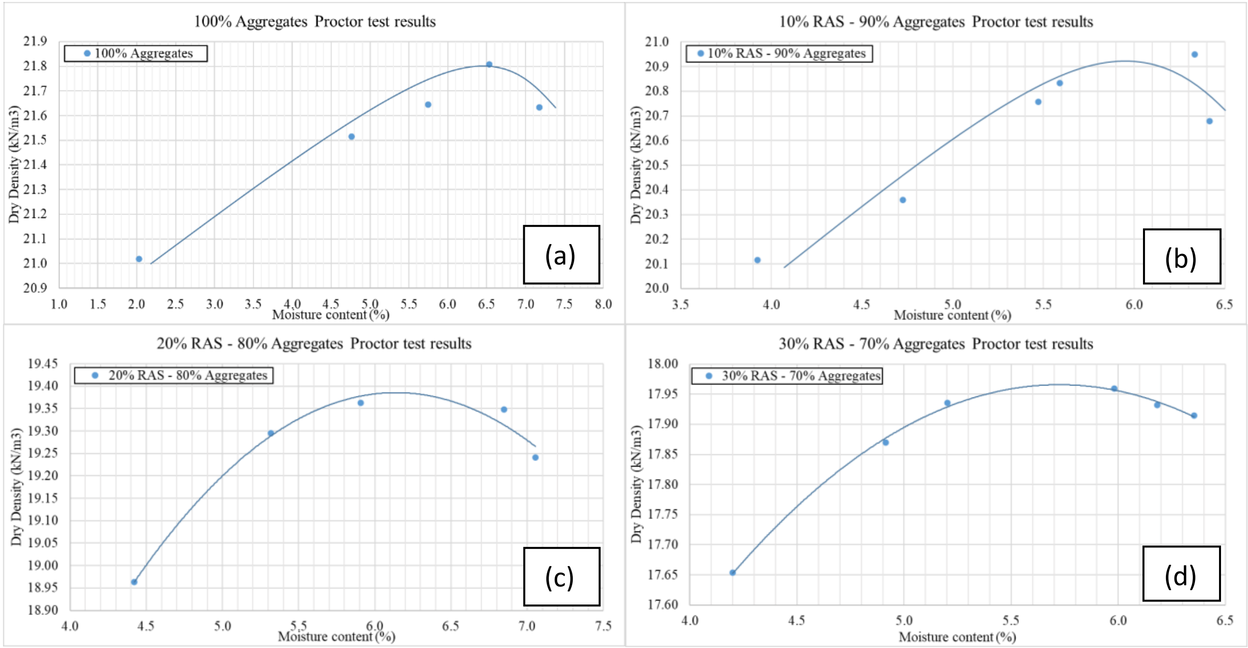
## Proctor test of granular materials

A modified Proctor test was done for mixtures with different percentages of RAS following ASTM D1557[33] to determine OMC (the moisture content which results in the maximum dry density (MDD) for the mixture). First, the aggregates were oven dried at 110°C and cooled to room temperature before mixing with RAS. Different percentages of water (4%, 5%, 6%, 7%, and 8% by weight of aggregates) were added to the mixtures, and the samples were compacted with a Proctor test hammer, which has a mass of 4.5 kg, in 5 layers with 56 blows on each layer. The MDD of each sample was calculated and shown in Table 5. Figure 7 present dry density versus moisture content plots for all mixtures. MDD shows a decreasing trend with a higher amount of RAS added, indicating that mixtures with higher RAS contents are not compactable enough compared to the lower concentrations. The MDD and OMC determined based on Proctor test results were used when conducting CBR tests on the samples.

Table 5. Modified Proctor test results for mixtures containing different amounts of RAS

| Mixture ID | OMC (%) | MDD (kN/m3) |
|---|---|---|
| 0% RAS | 6.5 | 21.80 |
| 10% RAS | 6.1 | 20.93 |
| 20% RAS | 6.1 | 19.39 |
| 30% RAS | 5.7 | 17.96 |

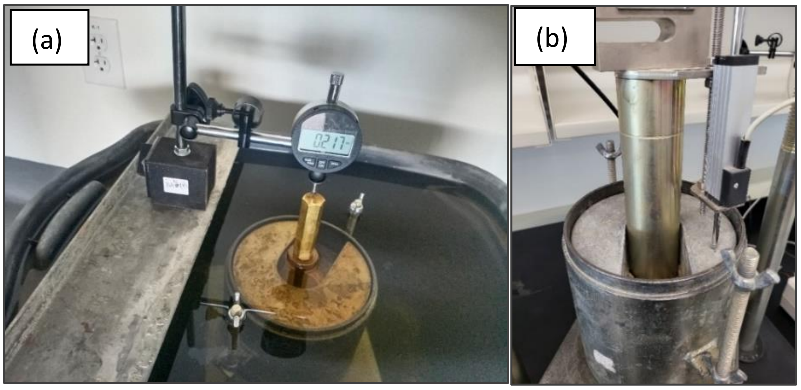
Figure 7. Proctor test results for aggregate samples with (a) 0%, (b) 10%, (c) 20%, and (d) 30% RAS



## CBR test

Dry and soaked CBR tests were done on all mixtures following the procedure described in ASTM D1883-21[30]. First, the aggregates were oven-dried overnight at 110°C and mixed with different amounts of RAS at their OMCs. Water was added to the aggregate-RAS mixtures, and the samples were mixed until uniform. The mixtures were poured into the compaction mold in five separate layers. Each layer was compacted with the specified number of blows (three different compaction levels: 10, 25, and 56 blows) with a modified Proctor hammer. The dry samples were tested right after compaction; however, soaked samples were kept in a water bath for 96 ± 2 hours before testing. After soaking, the samples were tested with a CBR machine. The forces required to penetrate 0.1 in and 0.2 in into the sample were recorded and used to calculate the CBR value. Figure 8 shows the CBR mold in the water bath and the setup for the CBR test.

Figure 8. (a) Sample soaking in water prior to CBR testing; and (b) CBR test setup



The CBR results for both dry and soaked samples prepared using different RAS contents are included in Tables 6 to 8 for compaction with 10, 25, and 56 blows. The CBR values signify the stress of the samples for a penetration depth of 0.1 in. The higher the material compaction, the higher the CBR value will be.

For use as a base course, the minimum CBR value for a mixture should be 80%[46]. A graph of corrected CBR value versus dry density is shown in Figure 9a for the mixtures with different percentages of RAS.

Table 6. CBR results (compaction with 10 blows) for dry and soaked samples with different RAS content

| Conditioning | RAS Content (%) | 10 Blows | | | |
|---|---|---|---|---|---|
| | | Dry Density (gr/cm$^3$) | % Compaction | Corrected CBR | STDEV |
| Dry | 0 | 2.23 | 100 | 98.3 | 20.53 |
| | 10 | 1.99 | 93 | 39.8 | 1.79 |
| | 20 | 1.84 | 93 | 12.4 | 0.02 |
| | 30 | 1.67 | 91 | 8.4 | 0.61 |
| Soaked | 0 | 2.23 | 100 | 106.4 | 17.69 |
| | 10 | 1.98 | 93 | 35.1 | 2.28 |
| | 20 | 1.89 | 96 | 15.7 | 2.35 |
| | 30 | 1.61 | 88 | 6.0 | 0.60 |

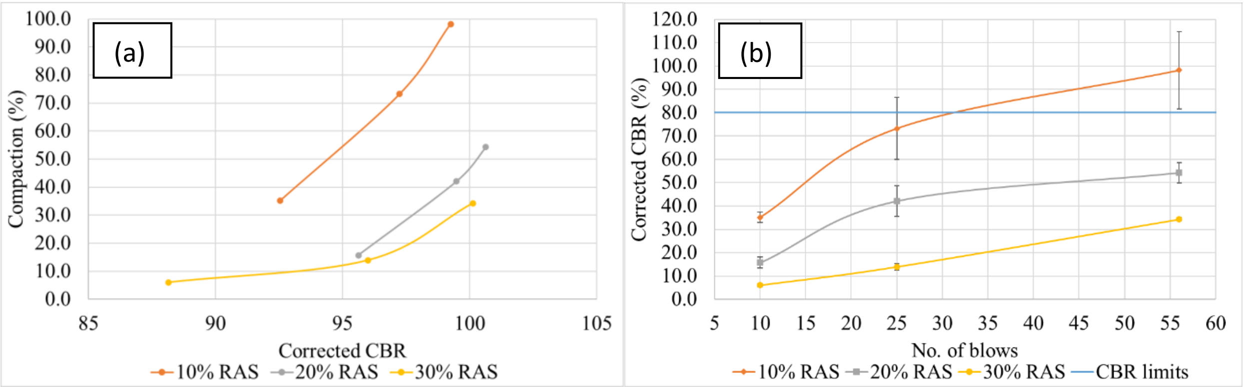
Table 7. CBR results (compaction with 25 blows) for dry and soaked samples with different RAS content

| Conditioning | RAS Content (%) | 25 Blows | | | |
|---|---|---|---|---|---|
| | | Dry Density (gr/cm$^3$) | % Compaction | Corrected CBR | STDEV |
| Dry | 0 | 2.24 | 100 | 117.0 | 4.75 |
| | 10 | 2.07 | 97 | 84.6 | 18.97 |
| | 20 | 1.91 | 96 | 29.0 | 4.19 |
| | 30 | 1.78 | 97 | 18.3 | 2.99 |
| Soaked | 0 | - | - | >100 | - |
| | 10 | 2.08 | 97 | 73.3 | 13.21 |
| | 20 | 1.97 | 99 | 42.1 | 6.53 |
| | 30 | 1.76 | 96 | 13.9 | 1.36 |

Table 8. CBR results (compaction with 56 blows) for dry and soaked samples with different RAS content

| **Conditioning** | **RAS Content (%)** | **56 Blows** | | | |
|---|---|---|---|---|---|
| | | **Dry Density (gr/cm$^3$)** | **% Compaction** | **Corrected CBR** | **STDEV** |
| Dry | 0 | 2.27 | 102 | 123.7 | 15.23 |
| | 10 | 2.10 | 98 | 109.7 | 12.90 |
| | 20 | 2.00 | 101 | 52.2 | 3.44 |
| | 30 | 1.85 | 101 | 30.5 | 5.02 |
| Soaked | 0 | - | - | >100 | - |
| | 10 | 2.12 | 99 | 98.2 | 16.63 |
| | 20 | 1.99 | 101 | 54.3 | 4.40 |
| | 30 | 1.83 | 100 | 34.3 | 0.73 |

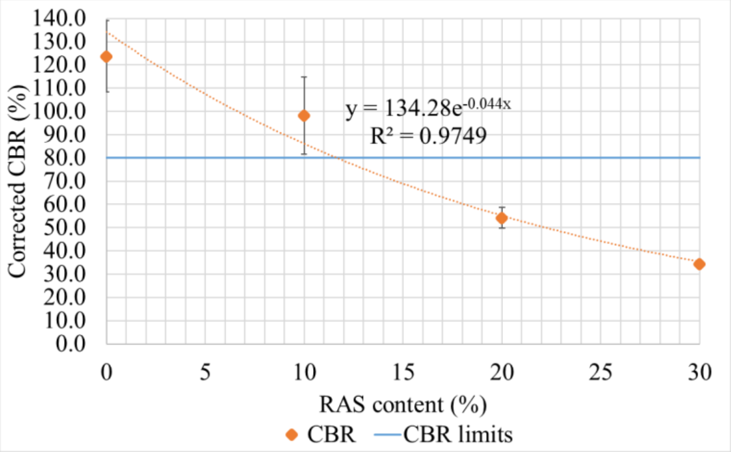
Figure 9. (a) Corrected CBR versus dry unit weight (as molded) and (b) Corrected CBR vs. number of blows used to compact samples for aggregate mixtures with different RAS content



Based on the results from Tables 6 through 8 and Figure 9b, the CBR was observed to decrease from over 100% for the mixtures with no RAS (0%) to 6% for the mixture containing 30% RAS (for the sample compacted with 10 blows, the lowest compaction). A similar decrease was observed for samples compacted with 25 and 56 blows, dropping from over 100% CBR to 14% and 34%, respectively. Considering a minimum acceptable CBR of 80% for a granular base layer (at a compaction level of 56 blows for soaked samples)[7, 39], only mixtures containing 10% RAS for the soaked samples met this criterion, with CBR values of 98.2%. The mixture containing 20% RAS is the closest to the CBR limit of 80% (54.3% for the soaked samples at 56 blows). The compaction percentage, defined as dry density of the compacted sample over MDD for the samples, shows a decrease for samples compacted with less blows, resulting in a decreasing trend of dry unit weight as molded (Figure 9a). Three points on each graph are representing 10, 25 and 56 blow with a decreasing trend.

Figure 10 shows the prediction of the RAS content for which CBR values is within the base course required limits (100% to 80% CBR[7, 39]). These values are only acceptable for the existing project and the materials described and tested in this research. Further analysis is required for any changes to the materials.

Figure 10. Corrected CBR vs. RAS Content



## Conclusions and Recommendations

This study was aimed for a comprehensive literature review on use of RAS material in road construction and preliminary tests on use of processed RAS material in a base course. Based on the findings from literature review and experimental research, the following conclusions and recommendations are drawn along with limitations in the project.

### Literature Review Conclusions:

- Incorporation of RAS in construction projects has multiple benefits where the environment is concerned such as sustainability, less waste in landfills, and preservation of raw materials[5, 16, 18]. However, the use of RAS in projects needs to be balanced in the context of potential negative impacts, including ground water and wildlife effects, leaching of PAHs, and asbestos exposure[6, 12, 15, 17, 19, 21]. Also, RAS can have financial benefits in certain projects[6, 14, 15].
- The use of RAS was reported to be effective for dust control, noise control, and reduction of road maintenance when used in the surface layer[5, 15, 19, 20].
- Having a larger target aggregate size was reported to cause separation in RAS-aggregate mixtures and lessen cohesivity in pavement structures[7, 22, 24]. Different sizes of RAS can influence the properties of the granular material. Larger RAS, like large aggregates, causes material separation[28].
- Materials with an initially high CBR value (more than 100%) decreased in stability when RAS was added[28].
- RAS was shown to be most effective when mixed with materials such as clay, where the addition of RAS resulted in an increase in stability (as measured by resilient modulus test)[7, 39].
- The addition of by-products and waste materials such as fly ash, bottom ash, and foundry slag to RAS-aggregate mixes reduced the compressive characteristics that RAS tends to have when mixed with aggregates[34].
- Multiple studies expressed support for the use of RAS mixtures in granular layers[7, 22,28, 34, 39].

### Laboratory Testing Conclusions:

- The optimum moisture content and maximum dry density for aggregate/RAS mixtures were found to decrease with increasing RAS content as determined by the Proctor test.

- California bearing ratio test results of the samples containing mixtures of granular RAS and aggregate indicate that increasing the RAS content decreases the strength of the material.
- The maximum RAS content that can be used in the base course while maintaining the strength within acceptable limits (80% CBR value or higher) was determined to be 10% RAS for the aggregate and RAS materials used in the laboratory tests conducted for this research.
- If different gradations of aggregate or RAS are used, this would require additional investigations to accurately determine acceptable RAS content (so that strength is maintained within acceptable limits).

A thorough review of the available literature shows that the properties of granular aggregates and RAS particle size affect the maximum RAS content. Laboratory testing is recommended for each specific aggregate and RAS material used in projects to determine the maximum RAS content in the mixture.
The laboratory testing conducted in this research was limited to only one type of RAS, one base course material. Other laboratory tests, including the determination of permeability and resilient modulus (which also affect the performance of base layers) are recommended for future studies.

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