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Improving the behaviours of expansive soils using recycled tyres

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ABSTRACT

This study reports the results of an experimental investigation into the use of ground rubber (GR) products, at varying contents and sizes/gradations, as a sustainable solution towards improving the inferior geotechnical attributes of a subgrade clay deposit located in Adelaide, South Australia. A total of seven soil–GR mix designs, consisting of one control (i.e., natural soil) and six GR-blended cases (at two GR contents and three GR sizes/gradations), were examined. As a result of GR inclusion, both the maximum dry unit weight and the optimum moisture content manifested a monotonically-decreasing trend; the exhibited reductions were in favour of both a higher GR content and a larger GR size. For any given GR size, the greater the GR content, the higher the developed UCS up to 5% GR, beyond which the dominant GR-to-GR interaction adversely influenced the UCS while still maintaining a notable advantage over the natural soil. The GR inclusions were able to control the soil's swelling potential. The higher the GR content and/or the larger the GR size, the higher the reduction in swelling. Based on the experimental results, a suitable soil–GR mix design was adopted and applied to stabilise a subgrade clay deposit from a local road in Adelaide, Australia. In-situ field density testing confirmed that the soil–GR mixture is a suitable subgrade material.

1 INTRODUCTION

In arid and semi-arid climates, the design and construction of infrastructure are often adversely affected by the presence of expansive/reactive soil deposits. A notable fraction of expansive soils consists of active clay minerals, such as montmorillonite, which are highly susceptible to seasonal fluctuations, and undergo significant expansion or contraction upon the addition or removal of water (Soltani et al. 2019a). The consequent cyclic increase and decrease in soil volume results in foundation distortion and wall cracking, and in the case of road infrastructure, undulating and cracking of pavements and embankment slumping. These issues are costly to maintain and repair, and also compromise road safety (Jones and Jefferson 2012). Accordingly, these adversities demand engineering solutions to mitigate the associated socio-economic impacts on human life.

The geotechnical engineer can either complete the design within the limitations imposed by the expansive soil or preferably alleviate the soil's adverse behaviours employing soil stabilisation techniques. The term "stabilisation" refers to any physical, chemical, biological or combined practice of altering the soil fabric to meet the intended design criteria (Winterkorn and Pamukcu 1991; Soltani et al. 2017). Conventional stabilisation practices often suffer from sustainability issues, attributed to high manufacturing and/or transportation costs, as well as environmental concerns due to greenhouse gas emissions. A sustainable soil stabilisation scheme can be characterised as one that maintains a perfect balance between infrastructure performance and the social, economic and ecological processes required to maintain human equity, diversity, and the functionality of natural systems. The transition to sustainable stabilisation warrants incorporating solid waste materials as an "additive" or "reinforcement" to expansive soils, while opting for non-conventional, environmentally-friendly chemical binders for further enhancements.

Discarded tyres are among the most significant and problematic sources of solid waste, owing to extensive production and their durability over time; for instance, annually, around 0.5 million tons of scrap tyres are stockpiled in Australia, annually (Li et al. 2018). Quite clearly, discarded tyre rubber materials are not desired at landfills, owing to their low mass-to-volume ratio, resilience, and the fact that they are rarely "flat-packed". These adverse characteristics, from a landfill perspective, also make them one of the most reusable waste materials for soil stabilisation practices. This is because, the rubber is resilient, lightweight, and possesses a rough surface texture. The latter, its rough surface texture, may potentially promote adhesion and/or induce frictional resistance at the soil–rubber interface, and thus alter the soil fabric into a unitary mass of enhanced strength resistance. The use of recycled tyre rubbers in geotechnical engineering dates back to the early 1990s, where theoretical concepts governing the mechanical performance of soil–rubber blends were put into perspective. Much like fibre-reinforced soils, the rubber particles randomly distributed in the soil matrix and when optimised in content and geometry (i.e., size/gradation and shape), enhance the inferior engineering characteristics of the host soil. The literature from this era, however, was mainly geared towards coarse-grained soils. As such, the rubber's capacity of improving the adverse behaviours of fine-grained soils, and expansive clays, in particular, remained rather vague. Ever since, several studies have documented the effects of rubber-reinforcement, with and without cementitious binders, on the physical and mechanical behaviours of expansive clays. The clay–rubber amending mechanisms can be attributed to the rubber content, with higher contents often producing a more pronounced reduction in the swelling capacity. Moreover, the rubber's geometrical features may also play an important role, and thus demands further investigation.

This study reports the results of a comprehensive experimental investigation, as well as a subsequent field trial, into the use of ground rubber (GR) products, at varying contents and sizes/gradations, as a sustainable solution towards amending the inferior geotechnical attributes of a subgrade clay deposit from a local road located in Adelaide, South Australia.

2 EXPERIMENTAL STUDY

2.1 Materials

The soil used in this study was collected from a local road in Adelaide, Australia. It manifested the same typical texture and plasticity features as commonly reported for expansive clays. The physical and mechanical properties of the soil were determined in the laboratory. The conventional grain-size analysis indicated a clay content (< 2 μm) of 43%, along with 37% silt (2–75 μm) and 20% sand (0.075–4.75 mm), dry mass basis. The liquid limit (as determined for 20-mm cone penetration depth using the 80 g–30° fall-cone device) and standard thread-rolling plastic limit were measured as w_L = 37.8% and w_P = 22.1%, respectively; giving a plasticity index value of I_P = 15.7%, such that the soil was classified as clay with intermediate plasticity (CI) in accordance with the Unified Soil Classification System (USCS). The free swell ratio (FSR) — a quantitative measure of clay mineralogy and hence the soil's expansive potential (Prakash and Sridharan 2004) — was obtained as FSR = 1.55, thereby indicating that the soil's clay fraction was mainly dominated by active smectite minerals, such as montmorillonite. In terms of expansivity, the FSR corresponded to a moderate expansive potential. The standard Proctor compaction test resulted in an optimum moisture content of w_{opt} = 19.7%, along with a maximum dry unit weight of γ_{dmax} = 16.9 kN/m^3.

Three types of commercially available tyre-derived ground rubber (GR) products, with varying sizes/gradations (hereafter designated as A, B and C), were used as the additives to partially replace the low-grade host soil. In terms of gradation, GR A, B and C were similar in size to fine (0.075–0.425 mm), medium (0.425–2 mm) and coarse (2–4.75 mm) sand, respectively. Other physical attributes included a specific gravity of G_s^{GR} = 1.09 for all three GR types, which is approximately 2.5-fold lower than that of the clay soil (G_s^S = 2.69). The chemical composition of the GR material, regardless of its gradation, was mainly dominated by styrene–butadiene copolymer and carbon black, with mass fractions of 55% and 25–35%, respectively.

2.2 Testing Program

The experimental program was carried out in two phases. The first phase involved investigating the soil's physical and mechanical properties by means of conventional laboratory tests — namely, Atterberg limits (i.e., liquid and plastic limits, and plasticity index), grain-size distribution (i.e., sieve and hydrometer analyses), standard Proctor compaction, and sediment volume (to measure the free swell ratio) tests. The results obtained from this phase were analysed to classify the soil in terms of its plasticity, mineralogy and degree of expansivity. The second phase involved investigating the effects of GR inclusion, in terms of both content and size, on the soil's compactability, shear strength and volume change behaviours. A total of seven soil–GR mix designs, consisting of one control (i.e., natural soil) and six GR-blended cases (at two GR contents and three GR sizes/gradations), were examined. This phase consisted of standard Proctor compaction, unconfined compressive strength (UCS) and oedometer swell tests. The results obtained from these three tests were then carefully analysed, and cross-checked with each other, to arrive at the optimum GR content and size.

3 EXPERIMENTAL RESULTS

3.1 Effect of GR on Soil Compactability

Figures 1a and 1b illustrate the variations of optimum moisture content w_{opt} and maximum dry unit weight γ_{dmax}, obtained in accordance with the standard Proctor compaction test (ASTM D698–12), against GR content for the natural soil and various GR-blended samples, respectively. For any given GR size/gradation, the greater the GR content, the lower the optimum moisture content and the maximum dry unit weight, both following a monotonically-decreasing trend with respect to GR content. Similarly, for any given GR content, an increase in GR size led to a further, yet slightly less pronounced, decrease in the soil's compaction characteristics.

Reduction in the compaction characteristics, particularly the maximum dry unit weight, advocates the use of GR as a sustainable, lightweight fill alternative to traditional quarried materials, such as sands and aggregates. The GR material's lower specific gravity of 1.09, as well as its hydrophobic character (< 4% water adsorption), compared with that of the soil grains, and active clay minerals, in particular, corroborate the observed reductions in the compaction characteristics (Cabalar et al. 2014; Signes et al. 2016; Soltani et al. 2019b).

Moreover, the compacted GR particles, though rather resilient, may gradually recover their initial shape due to the elastic rebound, thereby reducing the efficiency of compactive effort and hence leading to lower maximum dry unit weights (Soltani et al. 2019b). Quite clearly, the larger the GR size, the more pronounced the elastic rebound recovery and hence the lower the maximum dry unit weight.

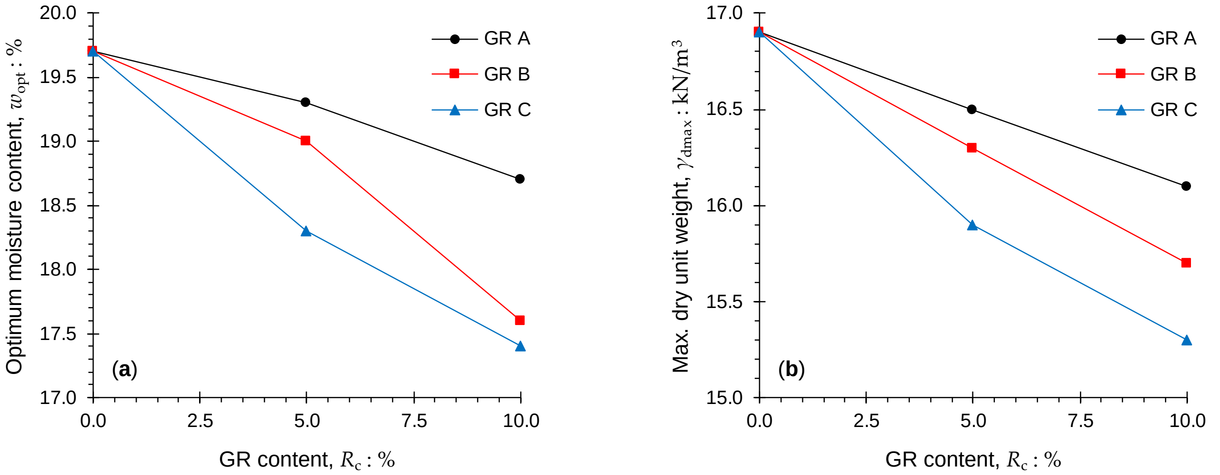

*Figure 1: Variations of (**a**) optimum moisture content w_{opt}, and (**b**) maximum dry unit weight γ_{dmax} against GR content for the tested samples.*

3.2 Effect of GR on Shear Strength

Figure 2a illustrates the variations of UCS, obtained as per ASTM D2166–16, against GR content for the natural soil and various GR-blended samples. For any given GR size, the greater the GR content, the higher the developed UCS up to 5% GR, beyond which the GR material was found to adversely influence strength development in the matrix while still maintaining a notable advantage over the natural soil. The only exception was 10% GR A (the fine rubber), which exhibited a lower UCS value compared with that of the natural soil. In terms of GR size, the addition of GR C, the coarse rubber, was found to consistently outperform the medium and fine rubber variants. The samples blended with 5% and 10% GR C resulted in UCS values of 248.5 kPa and 193.7 kPa, respectively. In other words, the soil's strength is improved, respectively, by almost 100% and 50% when mixed with 5% and 10% GR C.

Figure 2b illustrates the variations of axial strain at failure ε_u, a measure of the material's ductility, against GR content for the natural soil and various GR-blended samples. For any given GR size, the greater the GR content, the higher the axial strain at failure and hence the more ductile the sample's response to unconfined compression, attributed to GR's higher deformability compared with that of the soil grains. Similarly, the larger the GR size, the more ductile the sample's response to unconfined compression.

The elastic Young's modulus, denoted as E_s, is a measure of the material's stiffness in the elastic compression domain (Iyengar et al. 2013). In general, the variations of E_s, as shown in Figure 2c, exhibited a trend similar to that observed for the axial strain at failure; however, in an adverse manner. The greater the GR content and/or GR size, the lower the developed stiffness, attributed to GR's inherent lower stiffness compared with that of the soil grains.

As stated by the authors in their previous publications (e.g., Soltani et al. 2019a, 2019b), the GR inclusions can alter the soil fabric through improvements achieved in two aspects: (**i**) frictional resistance generated at soil aggregate–GR interfaces; and (**ii**) mechanical interlocking of soil aggregates and GR particles. The generated interfacial frictional resistance is a function of the soil aggregate–GR contact area, with greater contact levels offering a higher shear resistance against external forces. The greater the percentage of included GR particles and/or the larger the GR particle size, the greater the contact levels achieved between the GR particles and soil aggregates, and thus the higher the developed frictional resistance against compression. The mechanical interlocking of soil aggregates and GR particles is achieved during sample preparation (or compaction); it may induce sample adhesion by immobilising the soil aggregates undergoing shearing. Quite clearly, the more pronounced the achieved mechanical interlocking, the higher the resistance against compression. As such, this amending mechanism can also be ascribed to the GR content (and potentially the GR shape/elongation) — that is, the greater the GR content, the greater the number of potentially interlocked soil aggregates, and thus the higher the developed resistance against compression. In practice, however, these two amending mechanisms, interfacial frictional resistance and mechanical interlocking, only hold provided that the GR particles are well distributed in the soil medium, meaning that the GR particles do not cluster (or adhere to each other) during compaction. At high GR contents, the behaviour at some points within the blended sample could be governed by a dominant GR-to-GR interaction; this effect referred to as “rubber-clustering”, promotes a notable improvement in the sample’s ductility while offsetting the desired soil-to-GR interaction capable of enhancing its UCS. Such adverse effects were evident for all samples containing 10% GR, as the previously-improved UCS began to drop (see Figure 2a).

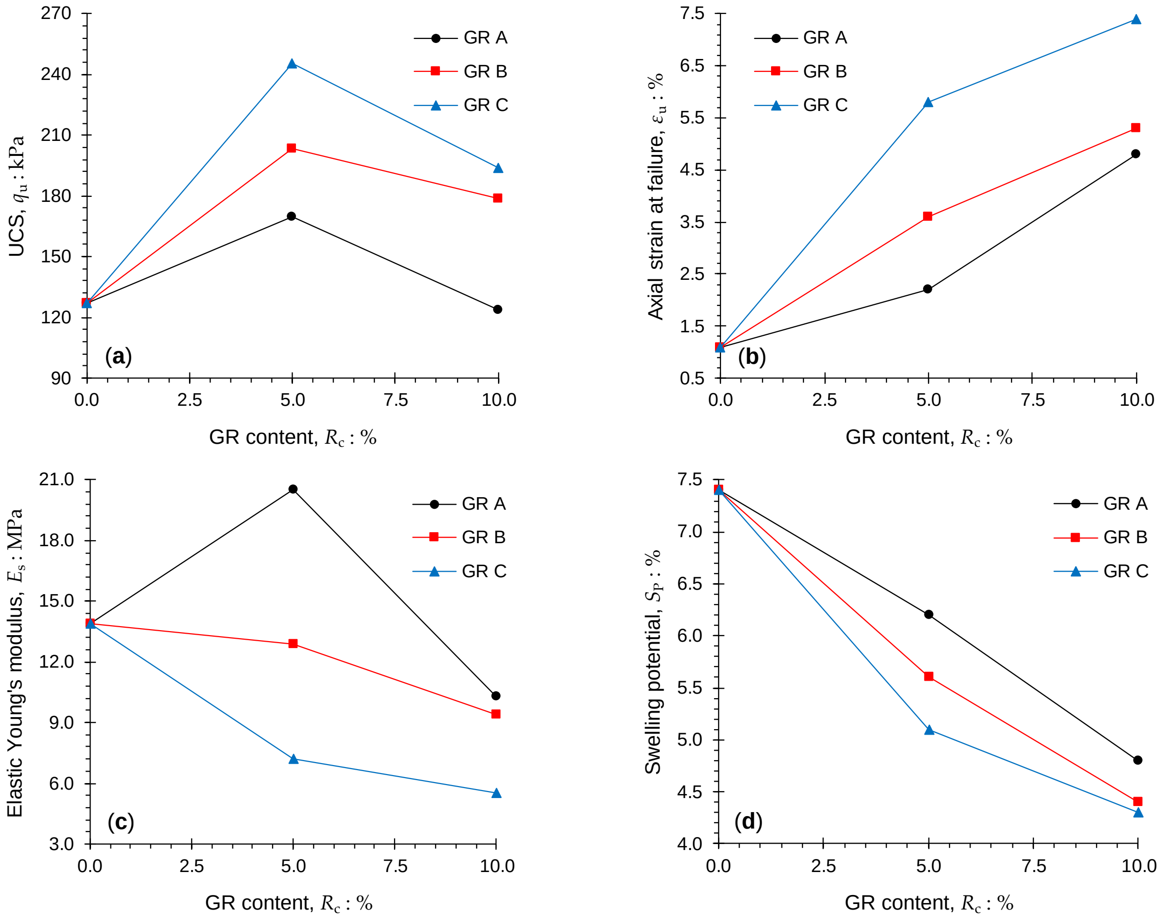

*Figure 2: Variations of (**a**) UCS q_u, (**b**) Axial strain at failure ε_u, (**c**) Elastic Young’s modulus E_s, and (**d**) Swelling potential S_P against GR content for the tested samples.*

3.3 Effect of GR on Swelling Potential

Figure 2d illustrates the variations of swelling potential S_P, obtained as per ASTM D4546–14 under a nominal overburden stress of 7 kPa, against GR content for the natural soil and various GR-blended samples. For any given GR size, the greater the GR content, the lower the swelling potential, following a monotonically-decreasing trend. Similarly, for any given GR content, an increase in GR size led to a further, but marginal, decrease in the swelling potential. In addition to the two amending mechanisms “interfacial frictional resistance" and "mechanical interlocking", the swelling potential is also a function of the soil's expansive clay content, with lower contents exhibiting a lower tendency for swelling. Consequently, an increase in GR content substitutes a larger portion of the expansive clay content with non-plastic, hydrophobic GR particles, thereby leading to a further decrease in the swelling potential. The swelling potential can be employed to specify the soil's degree of expansivity. The natural soil can be classified as "highly expansive" based on the classification framework suggested by Seed et al. (1962). The use of 10% GR A, B and C led to an improved "moderately expansive" classification.

3.4 Recommended Soil–GR Mix Design

Although all three GR variants were consistently effective at weaving the soil into a coherent matrix of restricted swelling (i.e., improvement in the swelling potential was in favour of higher GR contents), when excessively included, they could raise strength (and stiffness) concerns. Based on the experimental results, a GR content of 5% is able to satisfy a decrease in the soil's swelling potential while increasing its strength-related features, and thus can be deemed as the optimum choice. Moreover, GR B and C both outperform the finer GR A in terms of higher UCS and lower swelling potential values. Meanwhile, the use of GR B and C produced similar results with marginal differences. Accordingly, both GR B and C can be deemed as optimum GR sizes. Based on the experimental results, as well as discussions with the steering committee of the road subgrade stabilisation project, the inclusion of 5% GR C (with D_{50} = 3.12 mm) was recommended.

4 FIELD TRIAL

The optimum soil–GR mix design was applied to stabilise a subgrade clay deposit from a local road located in Adelaide, South Australia. The total length of the project area was 210 m, and it was divided into three different zones, each having a length of approximately 70 m. The GR stabilisation technique was implemented in two zones using a GR content of 5% (i.e., Zones A and C). The third zone, Zone B, in the middle of the road, was repaired by changing the asphalt layer. Zone B served as a control area for short- and long-term comparisons. The process of constructing the soil–GR mixtures is described below.

a. Spreading 5% GR uniformly across the pavement width. A spreader truck was used to enable the supply and distribution of the GR material (see Figure 3a). The spreader truck can cover 3.6 m of the road width both to the right and left. Three distinct passes were required to distribute a total of 5% GR on the surface.
b. Improving the native soil by mixing in GR using soil stabiliser equipment (Figure 3b). At this stage, the soil stabiliser machine used its milling and mixing rotor to mix GR into the existing clay soil layer (which had a moisture content of approximately 9%). The soil stabiliser equipment was able to inject water into the mixture to achieve the required moisture content. The equipment granulates the soil without loosening it to produce a homogenised soil–GR mixture. This process transformed the previous existing soil surface to a soil–GR layer which was ready for a new compaction process and subsequent paving. Then, 3% of lime was added to the clay–GR mixture to further enhance the subgrade's load-bearing capacity (see Figure 3c). The soil stabiliser machine was used to mix lime with the soil–GR layer.
c. Using multi-wheel rollers for the first pass after producing the soil–GR mixture (see Figure 3d), followed by up to six passes of a vibrating drum roller operating at a high amplitude and a low frequency (see Figure 3e), and then a smooth drum roller operating with a high wheel pressure (see Figure 3f) to knead the mixture into a compacted, evenly-textured soil–GR surface.
d. Then, class PM2 subbase material (Department of Planning, Transport and Infrastructure, 2018) was delivered to the site. For this, a wet-mixed of unbound granular PM2 was used. The PM2 was delivered using covered trucks, such that the material arrived on site at or near its optimum moisture content. The PM2 material was spread uniformly across the soil–GR layer using a road grader machine (see Figure 3g). The final PM2 mixture was achieved with a layer thickness of 100 mm.

e. Upon constructing the PM2 layer, steel-wheeled static rollers were used in the first pass, followed by approximately five passes of a vibrating drum roller operating at a high magnitude and a low frequency (similar to the compaction process of the soil–GR layer) (see Figure 3h). The compaction process was completed by means of pneumatic tyred rollers operating with a high compacting pressure to prepare a tight, evenly-textured base having a condition most beneficial for asphalt paving (see Figure 3i).
f. The PM2 layer was surfaced with 40 mm of bitumen-based asphalt, which is consistent with the traffic demand of the road (see Figure 3j).

The main objective of this field practice was to assess the feasibility of the GR stabilisation solution in terms of field implementation — that is, to understand the possible issues that may be encountered when mixing GR with the soil subgrade. It was observed that by implementing common paving practices, the GR particles can be mixed with the soil in a uniform manner — that is, potential mixing issues such as segregation and its adverse effects on compaction were not observed. Dynamic cone penetration (DCP) and field density tests were also performed on the base material. The results of field investigations demonstrated that the soil–GR could be used as a reliable subgrade material for road construction projects. Results of the field investigations will be reported in the near future.

*Figure 3: Field application of GR: (**a**) Spreading GR on the existing soil; (**b**) Mixing GR and the existing soil; (**c**) Adding lime to the soil–GR mixture; (**d**) Multi-wheel roller operating after completing the mixing process; (**e**) Vibrating drum roller operating at a high frequency and a low amplitude; (**f**) Smooth-drum roller operating at a high wheel pressure; (**g**) Spreading the PM2 material on the soil–GR–lime layer using a grader machine; (**h**) Compacting the base with a vibrating drum roller; (**i**) The road view after compaction of the base; and (**j**) Laying the asphalt layer on the road.*

5 CONCLUSIONS

This study has arrived at the following conclusions.

- As a result of GR inclusion, both the maximum dry unit weight and the optimum moisture content exhibited a monotonically-decreasing trend with increasing the GR content. Similarly, for any given GR content, an increase in GR size led to a further decrease in the soil's compaction characteristics.

- For any given GR size, the greater the GR content, the higher the developed UCS up to 5% GR, beyond which the dominant GR-to-GR interaction (i.e., rubber-clustering) adversely influenced the blended samples' UCS while still maintaining a notable advantage over the natural soil. The sample stiffness, however, manifested a monotonically-decreasing trend with GR content. Similarly, for any given GR content, an increase in GR size promoted a notable increase in the UCS and a decrease in stiffness.
- As a result of GR inclusion, the swelling potential exhibited a monotonically-decreasing trend with increasing the GR content. Similarly, for any given GR content, an increase in GR size led to a further, yet less pronounced, a decrease in the soil's swelling capacity.
- The GR material, at its optimum 5% content, was used to stabilise a subgrade clay deposit from a local road located in Adelaide, South Australia. It was concluded that by following standard paving practices, the GR particles can be mixed with the soil in a uniform manner, and potential mixing issues such as segregation and its adverse effects on compaction were not observed. This field application demonstrated that the soil–GR blend can be used as a reliable subgrade material in road construction projects.

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