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A Mixture of Waste Materials as a Construction Fill in Transportation Infrastructure

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Abstract. The reuse of waste materials in engineering projects is a sustainable concept that is being increasingly adopted in civil projects including the transportation infrastructure sector. A mixture of coal wash (CW), a waste produced by the coal mining industry, and rubber crumbs (RC), produced by shredding waste rubber tyres, is a possible alternative to natural quarried rock aggregates that are traditionally used in sublayers of transportation corridors. These materials have different properties than traditional aggregates and their geotechnical behaviour must be investigated before they can be confidently used in transportation infrastructure projects. This study particularly addresses the compaction characteristics of four CWRC mixtures (i.e. 0, 5, 10 and 15% rubber content) with a focus on the energy absorbing nature of rubber. The compaction energy must be increased to compensate for the energy absorbed by rubber and produce a compact packing of particles while keeping the breakage levels to a minimum. The strength and deformation properties of the mixture are also addressed through static triaxial tests under three confining pressures to simulate field conditions (i.e. 25, 50 and 75 kPa). The preliminary results showed that the mixture has sufficient strength for transportation sublayers that are not the main load bearing layers such as the subbase layer in roads and the capping/subballast layer in railways. Despite the compressibility of rubber which induces higher settlements, for the loads applied in practice at the level of a subbase or a capping layer, the expected settlements are within the allowable limits.
Keywords: Coal Wash, Rubber Crumbs, Transportation, Sustainability.

1 Introduction

The recycling of waste materials in ground engineering projects is becoming more popular in response to the strict environmental legislations associated with both natural quarries and waste landfills. Waste materials such as recycled aggregates from the demolition of existing structures, municipal waste materials such as glass and plastic, and by-products of industrial processes have been proposed by many studies over the past few decades to replace conventional quarried construction materials.

Coal wash (CW), a by-product of the well-established coal mining industry around the world, has been considered in past studies as a potential alternative for natural quarried aggregates [1-5]. For instance, [6] optimized a mixture of CW and steel slag to be used as a port reclamation fill. More recently, [7] proposed a mixture of CW and fly ash as subbase material for roads. Most of these studies highlighted that coal wash, being weaker than traditional aggregates, is highly degradable and undesirable high breakage levels were observed. To mitigate the degradation problem of CW, [8] introduced rubber crumbs (RC) into a mixture of CW and steel furnace slag and the mixture was optimized to be used a subballast layer in railways. Rubber crumbs also serve as an energy absorbing component which enhances the damping properties of the mixture [9, 10]. The effect of rubber inclusions on the geotechnical behaviour of traditional aggregates such as gravel and sand was also studied by numerous researchers in the past few years [11-19].

In this study, rubber is mixed with CW to create an energy absorbing layer as a potential construction fill that can be used in transportation sublayers, such as a the base/subbase layer in roads or the capping/subballast layer in railways. The compaction characteristics and the strength and deformation properties of four CWRC mixtures with 0%, 5%, 10% and 15% of added rubber are evaluated. The stress-strain response is studied using monotonic triaxial tests under three low confining pressures (i.e. 25 50 and 75 kPa) to mimic field conditions in transportation infrastructure. The effect of rubber on the strength and deformation properties of CWRC mixtures is addressed and these properties are compared with the requirements for the sublayers of transportation corridors.

2 Materials and Testing Program

CW used in this study was sourced from a colliery near Wollongong (NSW, Australia) and RC were procured from a tyre recycling company in Victoria. CW is a well graded material with a specific gravity of 2.25, while rubber shreds are much lighter having a specific gravity of 1.15. The particle size distribution (PSD) curves of CW and RC are shown in Fig. 1. Four CWRC mixtures were considered in this study having 0%, 5%, 10% and 15% of added rubber which corresponds to 0%, 4.76%, 9.09% and 13.04% rubber content, respectively, with respect to the total weight of the mixture. A previous study [8] optimized a mixture of CW, SFS, and RC as a capping material for railways and found that the optimum rubber content is close to 10%. Therefore, a range between 0% and 15% was selected knowing that more than 15% of rubber would overly reduce the strength of the material, make the blended mix overly compressible, and induce excessive axial settlement. Table 1 shows the physical properties of the CWRC mixtures and Fig. 1 shows that the PSD curves of all mixtures fall within the lower and upper limit for a subballast/capping material [20].

Table 1. Physical properties of CWRC mixtures.

Added rubber (%)	Grain size distribution (%)			Specific Gravity
	Gravel	Sand	Silt	
0	31.5	58.8	9.7	2.25
5	30.0	60.7	9.2	2.15
10	28.6	62.5	8.8	2.07
15	27.4	64.2	8.4	2.00

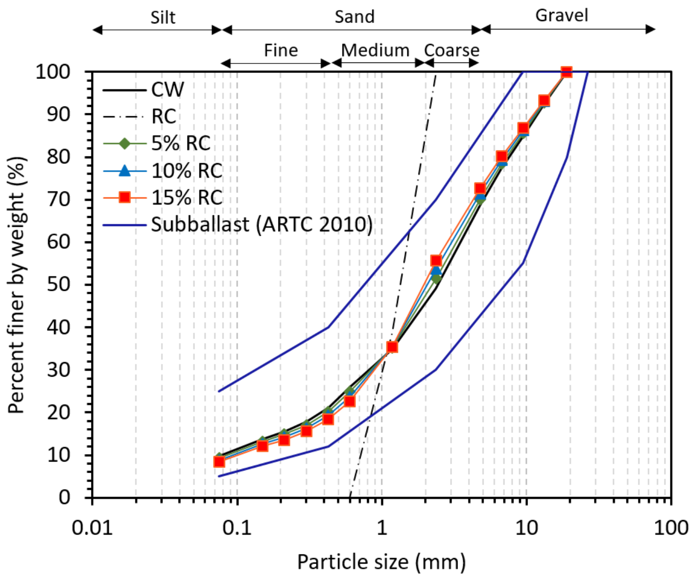

Fig. 1. PSD curves of CW, RC and CWRC mixtures

CW material was sieved using the wet and dry method [21] and each sample was prepared by mixing the exact weight of each size to reach the target PSD curve(Fig. 1). Then water was added to reach the target moisture content (≈ 9-10% for triaxial specimens) and the sample was left in a sealed container for 24 hours under constant humidity and temperature for consistent water distribution. Compaction tests were performed at standard Proctor, modified Proctor and three intermediate energy levels (Table 2). Static triaxial tests were performed in three stages. First the specimen (100 mm diameter and 200 mm height) was saturated by increasing the back pressure until a Skempton value greater than 0.97 was achieved. Then, the sample was consolidated at the target effective confining pressure (i.e. 25, 50 and 75 kPa). The shearing stage was then performed at a relatively slow constant strain rate of 0.1 mm/min to ensure fully drained conditions and the test was carried until the maximum strain limit of the equipment was reached, ≈20%. For the purpose of comparison, all the specimens were compacted to the same initial void ratio by increasing the compaction energy when rubber content increased.

Table 2. Details of the compaction tests (modified after [22]).

Energy level	Hammer weight (kg)	Layers	Blows/layer	Energy (kJ/m^3)
E_1	2.7	3	25	596
E_2	2.7	5	25	993
E_3	2.7	5	40	1588
E_4	2.7	5	50	1985
E_5	4.9	5	25	2703

3 Experimental Results

3.1 Compaction

The compaction curves under standard Proctor effort are shown in Fig. 2a. As expected, the dry density of the mixture decreases with increasing rubber content. This is partly due to the lower specific gravity of rubber particles. To eliminate the effect of the difference in unit weight of the components of the mixture and evaluate the effect of the energy absorbing nature of rubber on compaction efficiency, the void ratio is considered a better representation of the compaction efficiency [22].

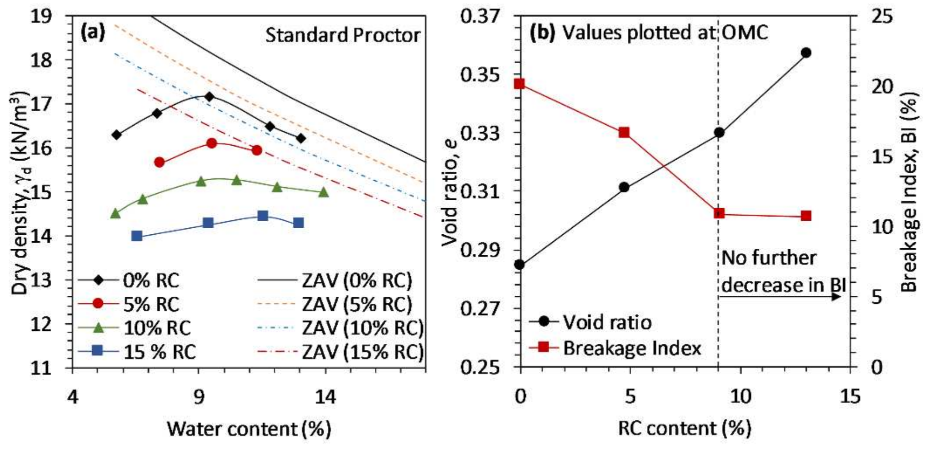

Fig. 2. Compaction of CWRC mixtures at standard Proctor effort (modified after [22])

Figure 2b shows that the void ratio at the optimum moisture content (OMC) increases almost linearly with increasing rubber content and becomes greater than 0.3 (i.e. the maximum acceptable void ratio for a capping layer [20]) when 5% RC are added to the mixture. Therefore, in practice, the compaction energy must be modified to compensate for the energy absorbed by the rubber. The effect of rubber content on the breakage index (BI) was also evaluated by quantifying the shift in the PSD curve after compaction [23]. Figure 2b shows that the BI decreases significantly when 10% rubber is added to the mixture. However, the change in the BI becomes negligible when more rubber is added. This indicates that for the size of rubber used, the degradation of particles reaches a first minimum at 10% rubber content and might not start to decrease again unless a much higher rubber content is used due to the inevitable breakage of larger particles in the mixture. Based on the above observations, the mixture with 10% of added rubber was compacted at higher energy levels up to modified Proctor to evaluate the effect of rubber on the compaction efficiency at higher energy levels.

Figure 3 shows the change in the void ratio and the BI with increasing energy levels for the CWRC mixture with 10% of added rubber.

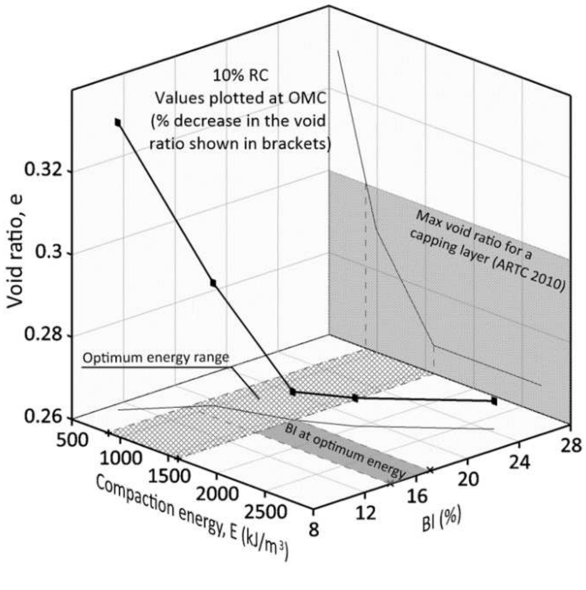

Fig. 3. Void ratio and Breakage Index vs. compaction energy (modified after [22])

The void ratio decreases significantly when the compaction energy increase from E_1 (standard Proctor) to E_3. After that point, no substantial change in the void ratio is observed when the compaction energy increases to E_4 and E_5 (modified Proctor). This indicates that in the energy range between E_1 and E_3, the excess energy transferred to the system is employed to compensate for the energy absorbed by rubber particles and to reach a compact rearrangement of particles. The mixture reaches an optimum packing which cannot be enhanced anymore at E_3 and for energies higher than E_3 the extra energy delivered to the system is either dissipated through rubber compression or through the degradation of CW particles. In fact, there is a sharp increase in the BI after E_3 which again shows that the mixture is over compacted and any excess energy would only lead to further breakage. Therefore, in practice the compaction energy must be selected with caution to reach an acceptable void ratio without causing excessive breakage of CW. Figure 3 shows that for just a 34% increase in compaction energy from standard Proctor (596 kJ/m^3) to 800 kJ/m^3, the void ratio of the mixture with 10% rubber content becomes less than 0.3. For instance, if 4 passes are required to compact an incompressible material like CW, a 34% increase in compaction energy is equivalent to 2 more passes which are easily achieved in the field. It is noteworthy that for this higher compaction energy, the BI of the CWRC mixture with 10% of added rubber (≈13%) is still less than the BI of the mixture with no rubber (i.e. CW) compacted under standard Proctor (≈20%).

3.2 Stress-strain relationship

Figure 4 shows the stress-strain relationship for all CWRC mixtures at three confining pressures (i.e. 25, 50 and 75 kPa). All the mixtures experience a post-peak softening behaviour and the peak deviator stress decreases as rubber is added to the mixture. This is attributed to the lower shear strength of rubber particles. However, even for a low confining pressure of 25 kPa, the strength of the mixture with 15% RC is still higher than 100 kPa, which is the expected load at the level of a subbase layer or capping/sub-ballast layer [8, 24-26]. Moreover, the ductility of the material is significantly improved when rubber is introduced into the mixture. From Fig. 4 it is observed that the post-peak softening modulus decreases when rubber content increases.

Figure 4 also shows that all mixtures reach almost the same critical state at 20% axial strain. This indicates that the inclusion of rubber particles affects the peak stress state only. In a CWRC mixture, three types of contact forces exist: contact between coal wash particles (CW-CW), contact between coal wash particles and rubber particles (CW-RC) and contact between rubber particles (RC-RC). For the low RC content considered in this study, we may assume that the number of contact points between rubber particles is negligible. At the peak stress state, the number of contact forces between coal wash and rubber crumbs affects the total stress that can be sustained by the mixture. However, at the critical state and when the sample has undergone dilation, the total number of contact points decreases and the number of contact points between rubber particles and CW particles becomes negligible compared to the total number of contact points, thus the behaviour at the critical state is mainly dominated by the frictional resistance between CW particles only. Previous studies also reported a unique critical state for sand-rubber mixtures for a rubber content less than 40% [15].

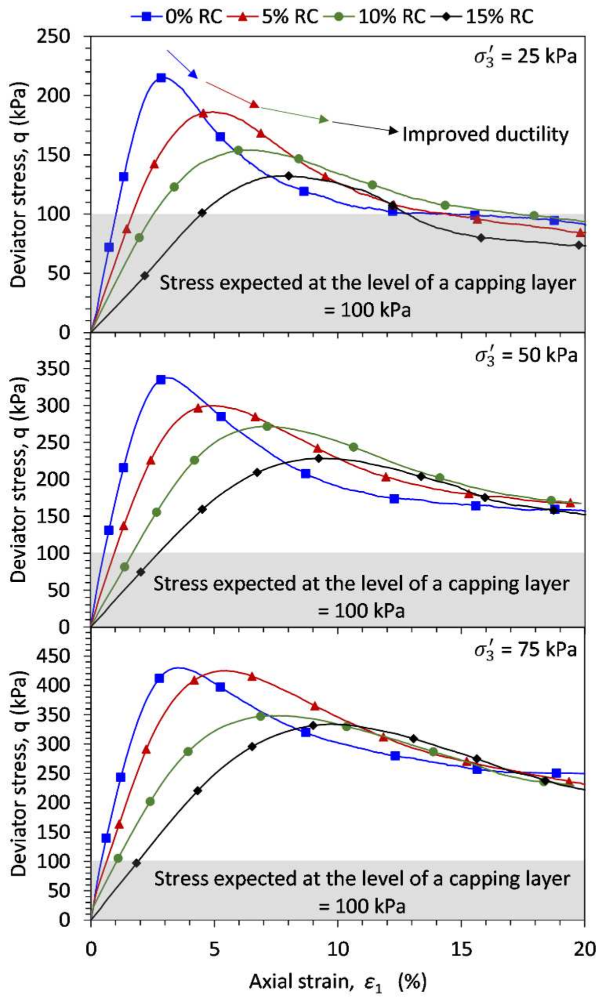

Fig. 4. : Stress-strain relationship of CWRC mixtures (modified after [22])

3.3 Volumetric strain

The effect of rubber inclusion on the maximum compressive volumetric strain is illustrated in Fig. 5. This volumetric strain does not represent the total change in the volume of the mixture, it only represents the change in the volume of voids as it is experimentally determined as:

$$e_v^* = \frac{\Delta V_v}{V_0} = \frac{\Delta V_w}{V_0}$$

where V_0 is the initial total volume of the sample, V_v is the volume of voids and V_w is the volume of water within the sample and for saturated conditions, $\Delta V_v = \Delta V_w$. Hence, the compression of rubber particles is not captured. The maximum compressive volumetric strain increases with increasing rubber content indicating a more contractive behaviour as rubber content increases. Rubber particles are highly deformable which facilitates the rearrangement of particles in the compression range. This results in a smaller volume of voids within the sample and hence a higher compressive volumetric strain.

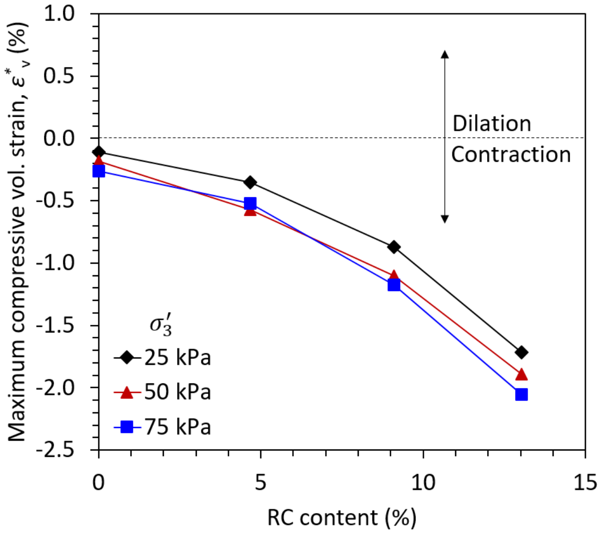

Fig. 5. Effect of rubber inclusion on the maximum compressive volumetric strain

3.4 Strength

Figure 6 shows the relationship between the peak friction angle and the rubber content for all CWRC mixtures. As expected, the peak friction angle decreases with increasing rubber content and this is attributed to the lower shear strength of rubber particles compared to CW. For transportation substructure layers which are not the main bearing layers such as the subballast layer in railways or the subbase layer in roads, a minimum peak friction angle of 45° is considered acceptable. The mixtures with 0%, 5% and 10% of added rubber show an acceptable peak friction angle for confining pressures of 25 kPa and 50 kPa. Only when the confining pressure is 75 kPa, the mixture with 10% RC falls below the minimum limit. However, the confining pressure usually encountered at depth of the subbase layer or the capping/subballast layer is close to 40 kPa [8, 26-28]. Therefore, for these conditions the mixture has an acceptable strength for a rubber content ≤ 10%.

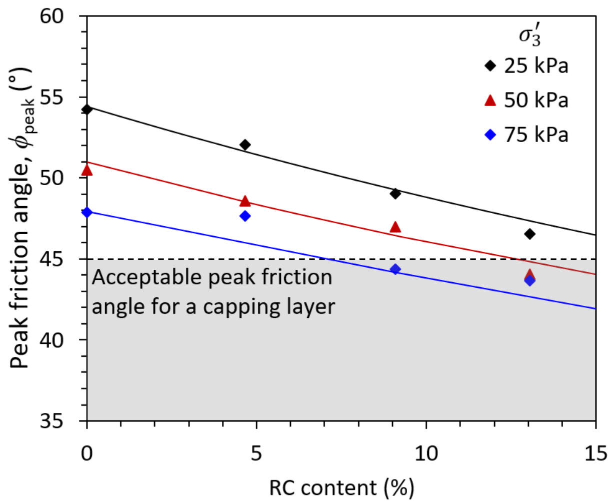

Fig. 6. Peak friction angle of CWRC mixtures (modified after [22])

3.5 Settlements

Rubber is highly compressible and when added to CW, it induces higher settlements under service loads. The maximum allowable axial strain for a subbase layer in roads or a capping/subballast layer in railways is 2%. Figure 7 shows the axial strain observed for a deviator stress of 100 kPa, which is the representative stress at the top of a subbase material [24-26] and at the level of a capping/subballast layer [8, 29].

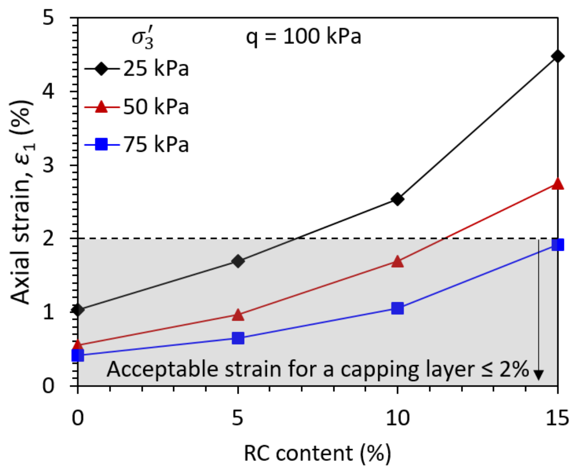

Fig. 7. Axial strain for a deviator stress of 100 kPa

The results show that the anticipated axial strain for the mixtures with 0%, 5% and 10% of added rubber is below the maximum limit for confining pressures of 50 kPa and 75 kPa and it becomes greater than 2% only when the confining pressure decreases to 25 kPa. The confining pressure expected at the top of a subbase layer or a capping/subballast layer usually ranges between 40 and 50 kPa [8, 26-28]. Therefore, up to 10% of added rubber can be used without inducing unacceptable settlements.

4 Conclusion

A series of compaction and triaxial tests were performed on four mixtures of CW and RC to evaluate its potential reuse as construction fill in transportation sublayers. The following conclusions are made:

- Despite the energy absorbing nature of RC, the mixture can be compacted to an acceptable level by increasing the compaction energy by 34%, i.e. multiplying the number of roller passes by 1.3, which is easily attainable in practice. It is not recommended to significantly increase the compaction energy, as this may only result in excessive breakage of CW without any additional increase in the dry density.
- The ductility of the mixture is significantly improved when rubber is added. This means that the material would not fail abruptly if the encountered loads become greater than the strength of the mixture and excessive immediate settlements can be avoided.
- For 10% of added rubber and for the confining pressures encountered in the field, the strength of the mixture is adequate for sublayers which are not the main bearing layers in transportation infrastructure such as the subbase layer in roads or the capping/subballast layer in railways.
- For the loads expected at the level of a subbase or capping/subballast layer, monotonic triaxial tests showed that the expected settlements are within the acceptable limit of 2%.

Although the properties of the proposed mixture were determined under static conditions, preliminary tests showed promising results and the proposed CWRC matrix could be adequate for a subbase in roads or a capping/subballast layer in railways. However, further testing under cyclic loading must be performed to fully characterize the material so it can be confidently used in transportation infrastructure projects.

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have been modified, whereby the original data has been reproduced with kind permission from Transportation Geotechnics.

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