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Sustainable Reuse of Coal Mine Waste: Experimental and Economic Assessments for Embankments and Pavement Layer Applications in Morocco

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Received: 7 September 2020; Accepted: 24 September 2020; Published: 26 September 2020

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Abstract: This paper deals with the potential reuse of coal mine waste rocks (CMWR) as an alternative material for road construction to conserve the natural resources and sustainable management of mining waste. The investigation was conducted through the determination of the chemical, mineralogical, geotechnical properties, and acid mine drainage formulation of CMWR as well as economic feasibility. This waste was used either alone for embankments and mixed with stabilizing agents fly ash (FA) and hydraulic road binder (HRB) for pavement applications. The experimental results confirmed that weathered CMWR can be successfully used alone as a sustainable alternative material for the embankment. Furthermore, the use of stabilizing agents in the following ratio CMWR:FA:HRB = 80:20:5 allow the use of CMWR in road sub-base layers for high-traffic pavements. Also, the environmental investigations showed that CMWR does not present any potential contaminating risk on the surrounding environment and most of the pyrite particles were already oxidized. Therefore, the environmental impact of acid mine drainage produced by pyritic waste throughout its life cycle can be neglected. Finally, an economic case study confirmed the workability of CMWR reuse in a radius of 29 km around their dumps by resulting in a lower cost compared with conventional materials.

Keywords: coal mine waste management; coal gangue; acid-mine drainage; sustainability; stabilization/solidification; road construction

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1. Introduction

The coal mining industry was significantly developed as it was the key to global industrialization. Worldwide coal production was estimated to be more than 7 billion tones in 2018 alone [1]. However, coal mining is always accompanied by the generation of large tonnages of mine wastes with potential impacts on the environment [2]. These impacts could take the form of waste dump instability, self-heating of residual coal and related accidents [3], acid mine drainage due to the oxidation of sulphides [4], water pollution [5], air pollution [6], and many other impacts [7].

In the framework of the circular economy and sustainable development objectives, coal waste rocks could be considered as alternative materials in the construction sector instead of pollution and risk sources. This solution will lead at once to the conservation of finite natural resources extensively used in the construction field and to reduced environmental impacts related to these wastes.

Many examples have been developed to valorise, reuse, dispose, and recycle these solid wastes in many fields including, construction and building materials. For example, Gruchot et al. [8] showed the influence of compaction on the shear strength of unburnt and burnt coal wastes without/with fly ash (FA) using triaxial compression tests. The tests and the stability calculations showed that the tested waste materials are useful for earth construction purposes. It was found that the shear strength parameters depend on compaction pressure. The highest values of the internal friction angle were obtained for the burnt coal waste, slightly lower for the mix, and the lowest for the FA. Kuranchie et al. [9] valorized mine tailings, waste rocks, fly ashes, and slags in construction material for highway and railway embankments. It was concluded that mine tailings alone and mixed with fly ash mine wastes can be favourably used as road embankment materials cost-effectively and sustainably. Also, the coal mine waste rocks (CMWR) wastes were successfully interred for the production of eco-friendly fired bricks at a laboratory scale [10,11], in the production of cement [12,13] and asphalt concrete products [14,15].

The present paper assesses the potential sustainable use of CMWR as an alternative material for road construction. The feasibility of using CMWR alone in embankments was investigated, and leaching and swelling properties were evaluated and discussed. For this purpose, toxicity characteristic leaching procedure (TCLP) and oedometer tests were carried out. The influence of FA and hydraulic road binder (HRB) addition on the behaviour of the designed mixes in terms of mechanical strength for the proposition of its application as pavement materials was also assessed. To achieve this aim, geotechnical, chemical, mineralogical and environmental tests were performed on raw CMWR, FA and HRB samples, and the mixed materials at various proportions. Regarding the economic aspect, the overall cost of using CMWR in embankments with a comparative study with conventional materials was also performed.

2. Materials and Methods

2.1. Materials

Samples of CMWR were collected from an old weathered coal dump, located in Jerada city, Morocco. Important amounts of coal mine wastes were landfilled in different dumps (Figure 1). One old big dump extends on a surface of about 15 ha and presents a height of 95 m. Other recent dumps are found in many places around the city [11]. The dump is the result of long exploitation of coal deposits of the Jerada carboniferous basin of the Paleozoic massifs in the Horst Range.

Different samples were taken at a depth of 2 m from the top surface, middle and bottom of the heap (Figure 2). The field-collected samples were then mixed and homogenized in the laboratory and riffle-split into smaller sub-samples before further testing. FA samples were collected from the local thermal power plant in Jerada. The specific gravity and specific surface area were 2.32 and 0.3 m^2/g, respectively. The hydraulic road binder (HRB) was provided by a local cement plant. Conforming to NF EN 13,282 standard [16], the used HRB corresponded to class 4 binder based on its content in the clinker.

2.2. Test Methods

2.2.1. Testing Protocol for Raw Materials Characterization

A series of laboratory tests were performed on CMWR, FA and HRB samples. As unconventional materials with unknown applications in road techniques for Moroccan pavement design, the geotechnical characterization of the CMWR samples were codified based on the [17] standard. The particle size distribution was obtained by dry sieving method for an element with a diameter greater than 80 μm while a granulometric test by using sedimentation approach was performed for size fraction less than 80 μm following NF EN ISO 17892-4 standard [18]. The optimal moisture content (W_{OPN})

and maximum dry unit weight ($\rho_{d\ OPN}$) of CMWR were determined using the Proctor test according to NF P94-093 standard [19]. The specific gravity (Gs) was measured using a helium gas pycnometer. The calcium carbonate ($CaCO_3$) content measurements within CMWR sample were obtained based on NF P94-048 standard [20]. The plasticity index (P_I) of CMWR samples was achieved using the Atterberg limits test. The liquid limit (W_L) was measured using the Casagrande cup method while the plastic limit (W_P) was performed by a rolled thread method of NF EN ISO 17892-12 standard [21]. Regarding the methylene blue absorption test (*MBV*), the studied samples were sieved on 5 mm mesh under NF P94-068 standard [22]. The specific surface area (Ss) of the fine fraction was determined by using the Brunauer–Emmett–Teller (BET) method.

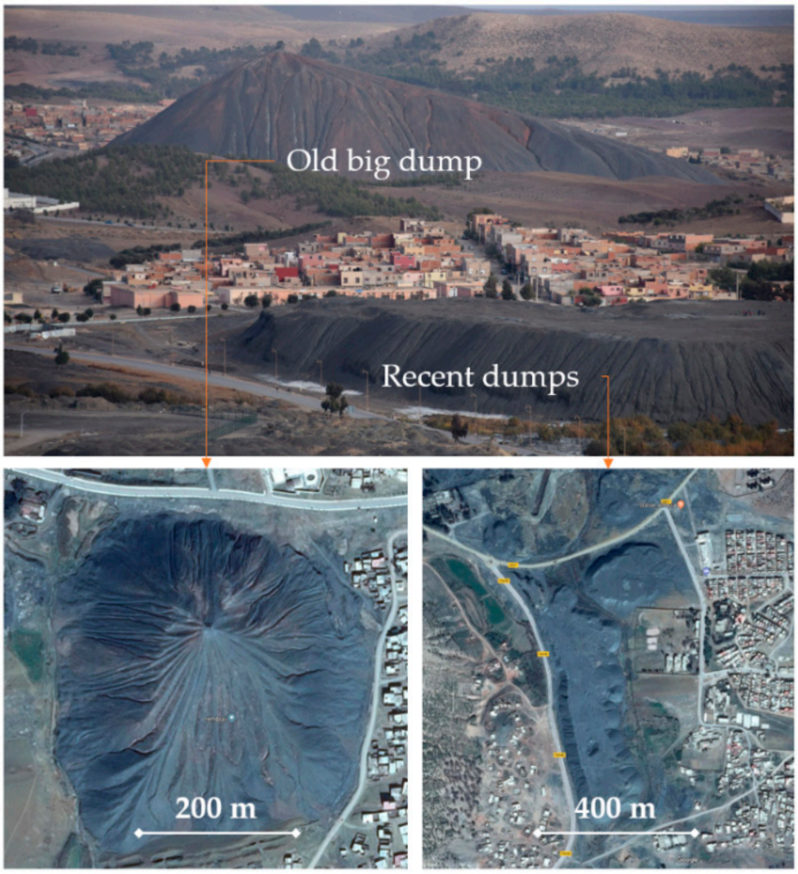

Figure 1. Old and recent coal dumps in the Jerada city.

Figure 2. Coal mine waste rocks (CMWR) sampling with a loader machine.

The compressive/swelling behaviour of the CMWR sample was determined using the oedometer test. This later was carried out on 0–20 mm size fraction at the optimal moisture content and the maximum dry density conditions of the standard Proctor test. The saturated specimen was subjected to axial stress levels ranging between 5 and 800 kPa, according to the XP P94-090-1 standard [23]. The swelling-shrinkage behaviour of clay fraction was assessed using many fundamental parameters such as the total specific surface area (*SST*). The *SST* value can be calculated based on the methylene blue absorbed value (Vb) by the clay fraction as expressed in Equation (1).

$$SST\left(\mathrm{m}^2/\mathrm{g}\right)(0-2\ \mu\mathrm{m}) = 20.93\ Vb\ (0-2\ \mu\mathrm{m}) \quad (1)$$

Furthermore, the swelling potential (Sp %) related to the presence of expansive clayey materials was estimated using Lautrin classification. Lautrin [24] proposed a classification of soil activity (A_{CB}) based on methylene blue adsorption value. The A_{CB} is defined as the ratio of 100 *MBV* to the clay fraction. However, the *MBV* value is obtained for the 0–5 mm fraction of the CMWR, including from the granulometric point of view clays, silts and sands. It is then interesting to be able to obtain the *MBV* on the clay fraction. To estimate the colloidal behaviour of CMWR, the methylene blue value is calculated for 100 g of clay fraction as follows (Equation (2)):

$$Vb\ (0/2\ \mu\mathrm{m}) = \frac{MBV(0/5)}{\%\ (0/2\ \mu\mathrm{m})} \quad (2)$$

To assess the sensitivity of CMWR material to fragmentation under mechanical stresses and immersion-drying cycles, the fragmentability (FR) and degradability (DG) coefficients were determined on the 10–20 mm aggregates fraction according to NF P94-066 [25] and NF P94-067 [26] standards, respectively. The resistance of CMWR aggregates to degradation by abrasion and wear was evaluated on 10–14 mm fraction using Los Angeles (LA) and Micro-Deval (MD) tests based on NF EN 1097-2 [27] and NF EN 1097-1 [28] standards, respectively. The Californian bearing ratio (CBR) which measures the resistance to punching and heavy machines traffic is a fundamental parameter to characterize the strength in the empirical pavement design. The CBR tests namely, the CBR at 4 days of immersion in water CBR(4i) and immediate bearing index (IBI) were determined conforming to NF P94-078 standard [29]. The IBI was determined for compacted specimens in the CBR mould at both modified and normal Proctor efforts without any soaking in water or overloading. The two parameters CBR(4i) and IBI reflect on the sensitivity to water and the immediate stability of the tested material, respectively.

A direct shear test was performed on a 0–5 mm size fraction of the CMWR material. The test sample was consolidated under drained shear conditions at various confining pressures (50, 100, and 200 kPa) according to NF-P94-071-1 standard [30]. The unconfined compressive strength (*UCS*) and the direct tensile strength (Rt) tests were conducted according to NF EN 13286-41 [31] and NF EN 13286-40 [32] standards, respectively. The cylindrical specimens were prepared at the optimum of the standard Proctor references and stored under standardized conditions at room temperature or subjected to water immersion at 20 °C before running tests at 28, 90 and 360 days.

On the other hand, the content of major and trace elements presented in the studied samples were measured using X-ray fluorescence (Bruker, Tiger Model, Bruker, Billerica, MA, USA) and inductively coupled plasma with atomic emission spectroscopy (ICP-AES) (Perkin Elmer Optima 3100 RL, Waltham, MA, USA). The crystalline phases were identified by the X-ray diffraction measurements (Bruker, AXS Advance D8, Bruker, Billerica, MA, USA). The Diffrac Plus EVA and TOPAS software programs (https://www.bruker.com/products/x-ray-diffraction-and-elemental-analysis/x-ray-diffraction/xrd-software/eva.html) were used to identify and quantify mineral species and abundances, respectively. The total sulfur (S) and total inorganic carbon (C) were determined by induction furnace analysis (ELTRA CS-2000, ELTRA, Haan, Germany). Moreover, the toxicity characteristic leaching procedure test (TCLP) EPA-1311 [33] was applied to determine the concentration of leached pollutants from the CMWR sample. The samples were prepared by crushed CMWR to pass through a 9.5 mm sieve, while the solutions were separated from the solid phase by filtration through a 0.45 µm. The obtained metal concentrations are then compared with the United States Environmental Protection Agency (US-EPA) limits.

2.2.2. Mix Design

To keep the designed mixes sustainable and economically competitive compared with the conventional materials, the performances of raw CMWR were enhanced by adding abandoned local FA in combination with a moderate amount of HRB. The choice of HRB was primarily motivated by the fact that it is suitable for the treatment of gravelly materials with fines (case of CMWR). It also has the following specifications: low hydration heat (more controlled cracking) and a clear improvement in the mechanical performance of mixtures.

Because a mix with content larger than 5 wt.% would not be economically feasible, the proportion of HRB was limited to 5 wt.%. Additionally, two formulations were tested. The first one comprised different proportions of CMWR and FA materials to achieve the target strength. The adopted process required a higher amount of CMWR to make the road project construction economical. The mechanical performances of the formulation tested in the laboratory with a proportion of FA lower than 15% were considered insignificant. For the second formulation design, the optimal mix of the first formulation tests was blended with different amounts of HRB ranging between 1 and 5 wt.% in order to improve the strength and stability after water immersion. The compositions of the considered mixes are listed in Table 1.

Table 1. Mix proportion of mixes design.

Use	Mix	Mix Proportion (wt.%)
Embankment	M0:CMWR	CMWR = 100
Road pavement layers	M1:CMWR:FA	CMWR:FA = 85:15
	M2:CMWR:FA	CMWR:FA = 80:20
	M3:CMWR:FA	CMWR:FA = 75:25
	M4:CMWR:FA:HRB	CMWR:FA:HRB = 80:20:1
	M5:CMWR:FA:HRB	CMWR:FA:HRB = 80:20:2
	M6:CMWR:FA:HRB	CMWR:FA:HRB = 80:20:3
	M7:CMWR:FA:HRB	CMWR:FA:HRB = 80:20:5

2.2.3. Use of Coal Mine Waste Rocks (CMWR) as Embankment Material

The potential use of CMWR alone as embankment material requires evaluating the specific geotechnical criteria as defined in local engineering guide. Maximum aggregate diameter, evolutionary behaviour in terms of grain size distribution and plasticity properties, environmental stability, swelling/compressibility behaviour and water sensitivity are the main recommended criteria by the Moroccan guide regarding embankment applications (GMTR) [34]. All these aspects were assessed using measurable parameters. Table 2 represents the design criteria with related parameters.

Table 2. Design criteria and quality monitoring parameters.

Criteria	Measurable Parameters
Evolutionary behaviour	Grain size distribution, *MBV*
Water sensitivity	CBR (4i)
Swelling/compressibility	Cc, Cs and $\sigma' p$
Environmental stability	Leaching of heavy metal

2.2.4. Evaluation of the Designed Mixes for Pavement Applications

The specimens of solidified materials were prepared by blending 0–20 mm size fraction of CMWR with FA, HRB and eventually water. The specific technical criteria should be checked for designing unconventional material in road paving use, among them, immediate stability, water sensitivity and long-term mechanical performance. To evaluate the ability of the designed mixes for capping layer use, the following requirements, as specified in the French technical guide [35], were adopted:

- CBR(4i) ≥ 20%
- CBR(4i) ≥ IBI
- Immersion resistance index (IR) ≥ 0.8 with, $IR = \frac{UCS\ (28+32i)}{UCS\ (60)}$

where, UCS (28 + 32i) is the unconfined compressive strength (MPa) measured after 28 days in standard conditions followed by soaking in water for 32 days at 20 °C, and UCS (60) is the unconfined compressive strength measured after 60 days in standard curing conditions. Moreover, according to the French guide, the pavement application requires the fulfilment of the following immediate stability conditions: IBI > 50 for the base layer and IBI > 35 for the sub-base layer.

For the average daily traffic of heavy vehicles from T5 to T1 (traffic classes) for the case of the foundation layers and from T5 to T2 for the base layers, the use of such material in pavement structure is mainly conditioned by the elastic modulus and direct tensile strength measurements at 360 curing days. It should be mentioned that the elastic modulus (E) test was not performed in this study, but it was estimated at desired age using the following equation (Equation (3)) which was recommended by ACI 318-95 [36] for normal weight concert:

$$E = 4.73\ (UCS)^{0.5} \tag{3}$$

where UCS is unconfined compressive strength (MPa) and E is the elastic modulus (GPa). This equation is the most suitable to this particle case as it tends to evaluate the elastic modulus taking into account the effect of coarse aggregate type on mechanical properties of CMWR (degradability). The estimated results of E and the measured Rt (direct tensile strength) values at 90 days curing time were reported in a specific abacus to predict the structural class of the designed mixes which must lead at least to the mechanical performance of zone "5" (zone 5 is the minimum structural class required) SETRA-LCPC [37]. Regarding the pavement layers application, the estimated results of E and the measured Rt values at 360 days ageing were reported in a specific graph to predict the structural class of the tested specimen which must lead at least to S2 class based on the NF P98-113 standard [38]. Table 3 gives the experimental plan for monitoring the proposed parameters.

Table 3. Design criteria and quality monitoring parameters for pavement applications.

Criteria	Monitored Parameter	
	Capping Layers	**Pavement Layers**
Compaction Characteristics	**Proctor Test Parameters**	**Proctor Test Parameters**
Immediate stability	IBI	IBI
Water sensibility	IR, CBR(4i)	IR, CBR(4i)
Mechanical performances (long- term)	(E,Rt) at 90 days ageing	(E,Rt) at 360 days ageing

3. Results

3.1. Raw Materials Characterization

3.1.1. Chemical and Mineralogical Characterization

The physical, chemical and mineralogical composition of the studied materials is highlighted in Table 4. Quartz (SiO_2), muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$) and chlorite ($(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2$, are the major crystalline mineral phases contained in CMWR while albite ($NaAlSi_3O_8$), titanite (TiO_2) and pyrophyllite ($Al_2Si_4O_{10}(OH)_2$) are present as minor phases. A low proportion of pyrite (0.3 wt.%) was also detected.

Table 4. Physical, chemical and mineralogical composition of CMWR, FA, and HRB materials.

Physical Properties		**CMWR**	**FA**	**HRB**
Specific gravity (Gs)		2.65	2.33	2.99
Specific surface area (BET) (m^2/g)		13.77	0.3	0.34
pH		7.1	11.5	10.7
Chemical Composition (wt.%)				
CaO		2.00	3.6	45
TiO_2		0.76	-	
SiO_2		59.5	52.3	15
SO_3				3
Al_2O_3		12.4	19.2	7
Fe_2O_3		4.3	7.4	4
MgO		1.34	3.1	1
Na_2O		0.64	0.2	0.5
K_2O		1.20	2.2	0.8
Inorganic carbon		7.2	1.1	
Total organic carbon		2		
Sulfur		0.47		
Loss on ignition		8.2	8.5	20
Mineralogical composition (wt.%)	**Formula**			
Quartz	SiO_2	40.8	38.4	8
Muscovite	$KAl_2(Si_3Al)O_{10}(OH,F)_2$	34		
Calcite	$CaCO_3$		2.1	26
Aluminate	$(CaO)_3\ Al_2O_3$			3
Alumino-ferrite	$(CaO)_4\ Al_2O_3\ Fe_2O_3$			7
Gypsum	$CaSO_4$-$2H_2O$	3		
Goethite	FeO(OH)	3.2		
Chlorite lib	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2$	6.3		
Albite	$NaAlSi_3O_8$	3.7		
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	7.7		
Titanite	TiO_2	0.8		
Alite	$(CaO)_3(SiO_2)$			34
Belite	$(CaO)_2(SiO_2)$			13
Pyrite	FeS_2	0.3		
Mullite	Al_5SiO_9	-	59.5	4

Concerning the characterizations of FA material, they are characterized by a high silica (SiO_2) content and low content of calcium oxide (CaO). Therefore, the class of the used FA is "F" fly ash based on the specifications of the [39] standard.

The HRB consisting mainly of CaO, SiO_2 and Al_2O_3 with the lesser amount by weight of SO_3, Fe_2O_3 MgO and Na_2O. The mineralogical analysis shows that alite $(CaO)_3(SiO)_2$, calcite $CaCO_3$ and belite $(CaO)_2(SiO)_2$ are the main crystalline phases present in the HRB material.

3.1.2. Acid-Mine Drainage Effects

As the presence of pyrite could affect the durability of the suggested solution, the behaviour of coal-derived pyrite surfaces was assessed using scanning optical microscopy (Figure 3). The observations showed that pyrite particles are present in two forms: framboidal and automorphic. The framboidal pyrite particles are highly reactive and could contribute to the formation of acid mine drainage. Fortunately, it was observed that the majority (more than 80%) of the analyzed pyrite particles are partially or completely oxidized giving rise to the formation of iron oxides in the form of goethite mostly included in alumino-silicate or coal minerals. This observation was predicted as the CMWR was altered and oxidized for more than 50 years. Consequently, the environmental impact of acid mine drainage associated with pyritic waste can be neglected.

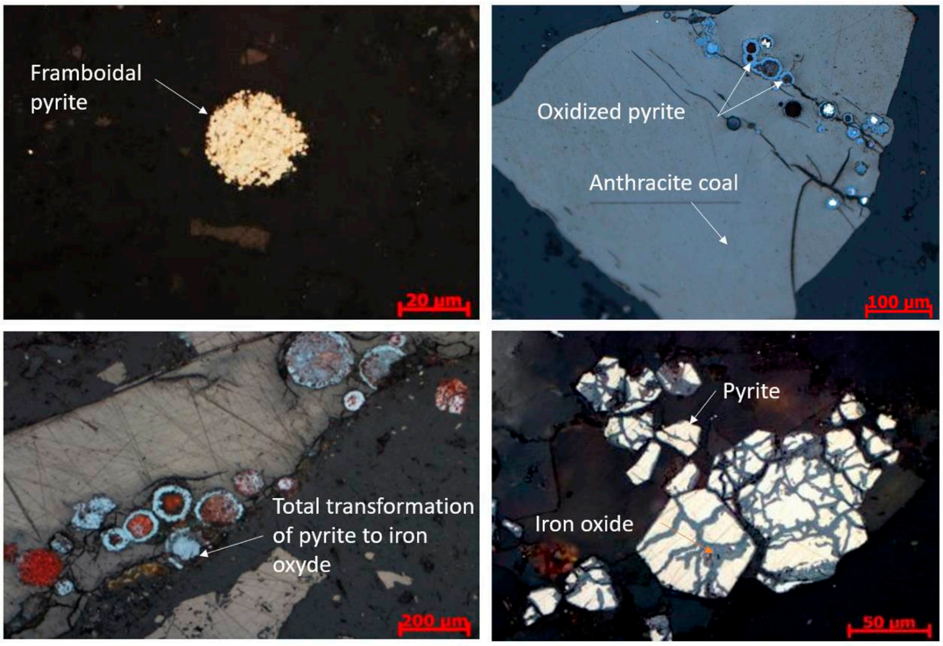

Figure 3. Optical microscopy observations of CMWR sample.

3.1.3. Compressibility Properties

The swelling/compressibility characteristics of the CMWR sample are presented in Figure 4. It is clearly shown that the settlement begins to appear just after a low loading strain and revealed an accentuated slope to which corresponds a compression index Cc of 0.15, which is still relatively low (Cc < 0.2). This result was expected since the dry density from which it prepared the specimen was high (19 kN/m^3), the proportion of organic matter was negligible (<2 wt.%) and the content of fine elements was limited. However, the shape curve indicates an important swelling index Cs of 0.04 with a pre-consolidation stress σ′p of 80 kPa.

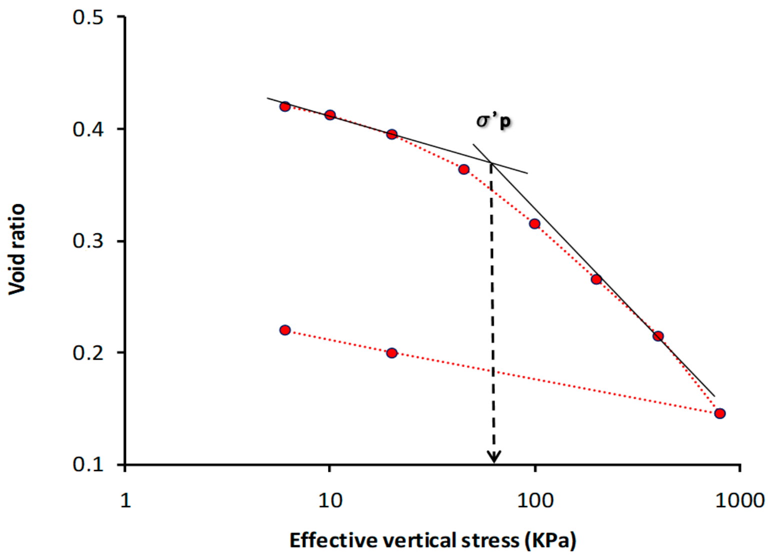

Figure 4. Compressibility curve of compacted CMWR material.

3.1.4. Geotechnical Characterization

The first step in investigating the CMWR characterizations was to identify the main geotechnical properties. The size distribution curves of CMWR, FA, and HRB samples are given in Figure 5. Regarding CMWR sample, the uniformity (Cu) and Curvature (Cc) coefficients were found equal to 255 and 2.95, respectively. Therefore, the CMWR was a well-graded granular material. The average grain size (D_{50}) of CMRW samples was 1.5 mm and the largest diameter of grain (Dmax) was 50 mm. The clay content and the percentage by weight of grain size less than 80 µm were 6.5 and 22.3 wt.%, respectively.

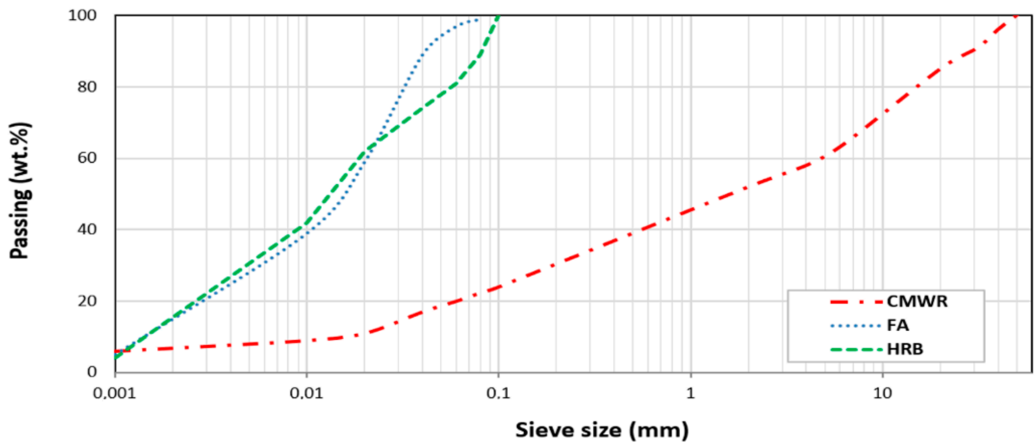

Figure 5. Grain size distribution curves of used materials.

For the granulometric composition of FA samples, it can be seen the average and maximum grain size were respectively 15 µm and 80 µm. Furthermore, FA contained a low proportion of clayey particles and 91 wt.% of passing through 40 µm mesh sieve. Concerning HRB, the largest particles size and clay content were 0.1 m and 3 wt.%, respectively.

The influence of compaction energy on the CBR(4i) and compaction characteristics of reconstituted CMWR material were examined. For this purpose, Proctor and CBR strength tests were conducted under standard and modified energies. Based on the results given in Figure 6, it can be noted that both CBR (4i) and maximum dry weight values under modified compaction energy are found to be greater than the under standard effort. Additionally, under modified proctor effort, a slight decrease in optimal moisture content was observed. This could be explained by the fact that increasing compaction energy leads to the largest amount of fine fraction and consequently to the lowest air voids ratio. The significant improvement (7.37%) in dry weight obtained by the modified Proctor energy and the low abrasive wear performance highlighted by fragmentability (FR) and degradability (DG) coefficients allowed us to conclude that the energy developed under the modified Proctor test is more appropriate for embankment compaction of CMWR material.

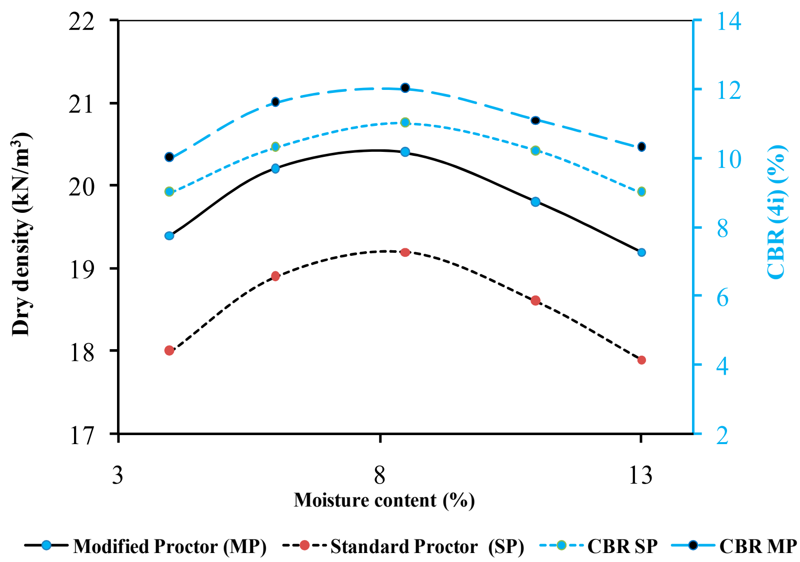

Figure 6. Proctor compaction energies of CMRW samples according to dry weight and CBR(4i).

The field compaction behaviour was simulated in the laboratory using an automatic Proctor machine under three controlled stress strains (0.6, 1.5 and 2.7 MPa). The particles size curves (Figure 7) obtained under different energies reveal a sensitive granulometric evolution towards the fine fraction. Nevertheless, this evolution reached an almost stable state when the compaction energy exceeds 1.5 MPa. Consequently, the energy developed by the standard Proctor test remains insufficient to ensure the quality of compaction without any possible risk of production of fine particles during the life of the road structure.

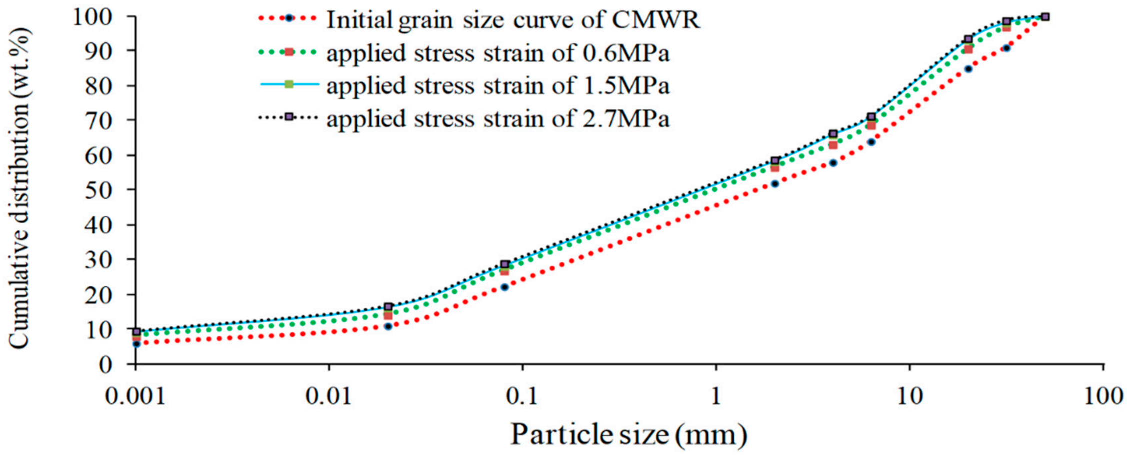

Figure 7. Evolution of grading curves of CMWR under controlled compaction energies.

The main geotechnical characteristics of the CMWR samples are summarized in Table 5.

The shear strength parameters, required for assessing the stability of the compacted CMWR structures, were evaluated on a 0–5 mm size fraction (represent 61 wt.% of total masse) using the consolidated drained shear test. The experimental results allow to identify an effective cohesion C'_P of 13 kPa and an effective friction angle of $\varphi'_P = 30°$. The C'_P value indicated a cohesive texture of the CMWR material which can be attributed to cementing phenomenon of the clay fraction.

Regarding the plasticity, the fine particles of the CMWR samples could be described as plastic clay, with important activity based on its clayey fraction ($A_C = 2.61$). The methylene blue value of 0.89/100 g showed moderate sensitivity to water variations of studied samples. To simulate the particles degradation under field conditions, the fragment ability and degradability tests were made on CMWR aggregates. These tests assessed respectively the sensitivity to break up and resistance under the effect of wetting–drying cycles. The FR and DG, that were respectively more than 7 and 20, indicated that the CMWR is a fragmentable and very degradable aggregate material within the meaning of the Moroccan technique guide [34].

LA and MD tests were carried out to evaluate the abrasion performance and friction properties of CMWR aggregates, respectively. The results reported in Table 5 confirm that the studied CMWR have both LA and MD results in more than 45%. They are therefore not suitable as pavement materials for road construction. These granular materials are easily fragmented into smaller particles. This causes an evolution in the grain size dimension inducing a change in their mechanical properties. This granulometric evolution under dynamic fragmentation makes the use of CMWR as an embankment material conditioned by sufficient compaction energy. This mechanical characteristic could be attributed to low hardness abrasion of muscovite minerals which generates a large amount of fine fraction under the action of mechanical stress. It can be concluded that the geotechnical and mechanical behaviour of CMWR aggregates relates primarily to their mineralogical composition.

From the results reported in Table 5, the studied CMWR belongs to the "B_{52}" category which corresponds to very silty sand and gravel materials with medium hardness. Thus, these materials can be used in the construction of road embankments following the compaction table as proposed by the French roadwork guide.

Table 5. Geotechnical properties of CMWR.

Standard Proctor Test	
Optimal moisture content (W_{OPN}), (%)	11.12
Maximum dry weight (ρd_{OPM}), (kN/m^3)	19
Modified Proctor Test	
Optimal moisture content (W_{OPM}) (%)	10.11
Maximum dry weight (ρd_{OPN}), (kN/m^3)	20.4
Shear Test	
Friction angle (φ′P), (degree)	30
Cohesion (C′P), (kPa)	13
Bearing Ratio Test	
CBR (4i), (%)	9
IBI, (%)	29
Atterberg Limits	
Liquid limit (WL,), (%)	42
Plastic limit (WP), (%)	25
Plasticity index (PI), (%)	17
Clay activity, (Ac)	2.61
Methylene blue value (*MBV*) (g/100 g) (0/5 mm)	0.89
Methylene blue value (*MBV*) (g/100 g) (<2 µm)	13.69
Total specific surface (m^2/g) (<2 µm)	286.53
Lautrin activity ACB (<2 µm)	210.61
Carbonate Content (%)	21
Oedometer Test	
Compression index, (Cc)	0.15
Swelling index, (Cs)	0.04
Preconsolidation pressure (σ′p),(kPa)	80
Mechanical behaviour	
Los Angeles, (LA), (%)	69
Micro Deval, (MD), (%)	77
Degradability coefficient, (DG)	18.7
Fragmentability coefficient, (FR)	11.4
Material classification (NF P 11-300)	B52

3.1.5. Swelling Behaviour

The swelling behaviour was assessed using the Lautrin activity and the total specific surface *SST* of the clay fraction. The ACB and *SST* parameters were equal to 210.61 and 286.53 m^2/g, respectively. The *SST* was close to that obtained by very swelling smectite. Consequently, the clay fraction of CMWR can be considered as harmful clay based on Lautrin classifications. Furthermore, the CMWR embankments were susceptible to swelling by hydration under pressure below 80 kPa (pre-consolidation). The swelling behaviour could be related to the presence of oxidized sulphate minerals (mainly gypsum) which are considered as an expansive mineral. The formation of sulphate results from the oxidation of pyrite particles in the presence of air and water. It can be concluded that the studied CMWR sample showed a slight compressive behaviour with significant potential of swelling.

In light of the above, the significant degree of granulometric evolution under various stress strains requires an intense compaction energy equivalent to that developed by the modified Proctor test. The consideration of stability measures during the implementation phase is also necessary. In this regard, to avoid disturbances in embankment undergoing drying-wetting cycles, it is advisable to provide containment with other selected materials as well as prescribing compaction at the near optimal moisture content (or more precisely, avoid dry compaction). Full-scale field investigations are also required to define the optimal compaction conditions.

3.1.6. Environmental Behaviour

The results of the toxicity characteristic leaching procedure (TCLP) test are summarized in Table 6. The concentrations of leached heavy metals and metalloids were mostly low and below the thresholds for granular wastes in landfill specifications [40]. Therefore, CMWR could be considered as non-hazardous waste. Also, it was proven from the studies of Battioui et al. [41,42] that a negligible amount of sulphate release was observed. The addition of fly ash as amendments led to substantial reduction of the sulphate release.

Table 6. Leaching behaviour of CMWR sample.

	As (µg/L)	Ba (µg/L)	Cd (µg/L)	Cr (µg/L)	Cu (µg/L)	Mo (µg/L)	Pb (µg/L)	Zn (µg/L)
CMWR	57	85	5	11	64	6.8	73	624
TCLP level limits	2000	1000	5000	-	5000	-	5000	2000

3.2. Evaluation of Designed Mixes for Road Pavement Use

3.2.1. Mechanical Properties

The effects of stabilization agents on the CMWR behaviour in terms of water sensitivity, immediate stability, and strength properties are given in Table 7. It should be noted that the experimental results reported in Table 7 correspond to the average values of three tested specimen and the calculated standard deviation for all mechanical performance tests still lower than 3% which reflects the low dispersion of the results. It is clear that the addition of 15 wt.% of fly ash increases slightly both IBI and CBR(4i) of raw CMWR, but the increase in FA proportion from 15 to 20 wt.% leads to significant growth in CBR ratios. For the mix M3, the addition of supplementary 5% FA does not influence the CBR ratios.

Table 7. Results of mechanical properties of designed mixes.

Mix	CBR Ratios		IR	*UCS* (MPa)		Rt (MPa)		*E* (GPa)	
	IBI (%)	CBR (4i) (%)		90	360	90	360	90	360
M0	29	11	1.18	-	-	-	-	-	-
M1	30	12	1.28	0.47	0.49	0.12	0.13	3.24	3.31
M2	35	17	1.31	0.5	0.54	0.16	0.17	3.34	3.48
M3	36	17	1.32	0.52	0.54	0.16	0.18	3.41	3.48
M4	39	31	1.48	1.59	1.61	0.21	0.23	5.96	6.00
M5	48	85	1.50	2.50	2.56	0.35	0.36	7.48	7.57
M6	53	189	1.52	4.26	4.4	0.44	0.46	9.76	9.92
M7	58	256	1.53	5.28	5.35	0.55	0.60	10.77	10.99

Generally, without HRB, the effect of FA remains below the requirements of the French guide regarding immediate stability condition. This could be attributed to low free CaO content present in FA material. All mechanical performances were found to be increased by raising the HRB concentration. The CBR(4i) was increased from 16% for zero content to 31%, 85%, 189% and 256% at a proportion of 1, 2, 3 and 5 wt.% HBR, respectively. This improvement can be explained by the chemical transformation and development of cement phases hydration due to the high amount of aluminosilicate minerals present in the CMWR sample. The stronger trend of increase in terms of elastic modulus and direct tensile strength was noted by increasing the HRB amount at different curing times.

3.2.2. Evaluation of Designed Mixes as Capping Layer Material

Figure 8 shows the predictive classification in terms of estimated elastic modulus *E* as a function of the measured direct tensile strength Rt of the designed mixes at 90 curing time. The results indicate that, among the four designed mixes, only the M4 mix does not belong to the minimum mechanical performance required (zone 5). Therefore, the proportion of 1 wt.% HRB does not allow direct use of CMWR:FA:HRB solidified material in capping layers. The M5, (CMWR:FA:HRB = 80:20:2), M6 (CMWR:FA:HRB = 80:20:3) and M7 (CMWR:FA:HRB = 80:20:5) mixes are, respectively, classified in the zone 4, 4 and 3 following the French technical guide specifications. Furthermore, the analysis of the results showed that the aforementioned mixes meet the water sensitivity and immediate stability requirements as described in Section 2.2.4. Consequently, mixes M5, M6 and M7 can all be used successfully as materials for the construction of capping layers.

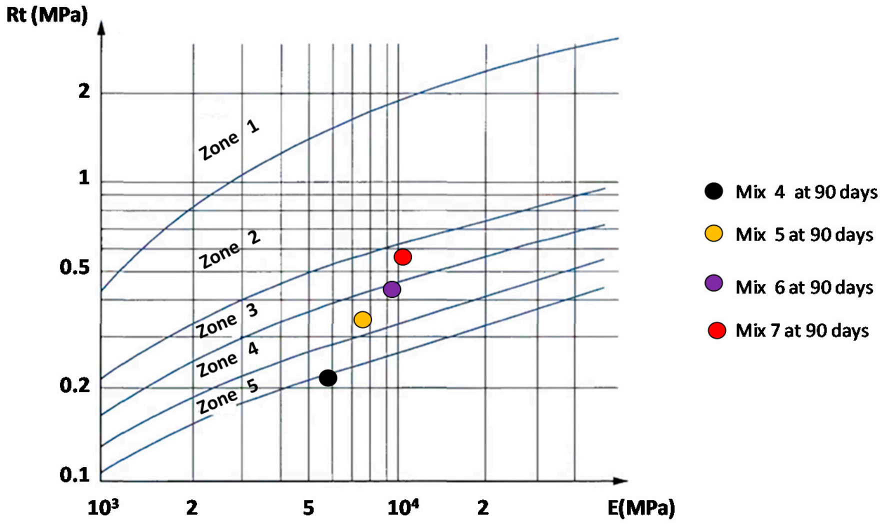

Figure 8. Classification zones of the designed mixes according to the (*E*, Rt) at 90 curing ages [35].

3.2.3. Use in Pavement Layers

The results obtained from compression strength measurements and elastic modulus prediction at 360 days ageing are illustrated in Figure 9. It is observed that only M7 mix is classified in the S2 class. Moreover, from Table 7 results, the M7 mix satisfies also the minimum requirements of immediate stability conditions for the pavement applications. Based on the NF-P98-113 standard [38], only M7 can be used in both foundation and base pavement layers for high-traffic pavements.

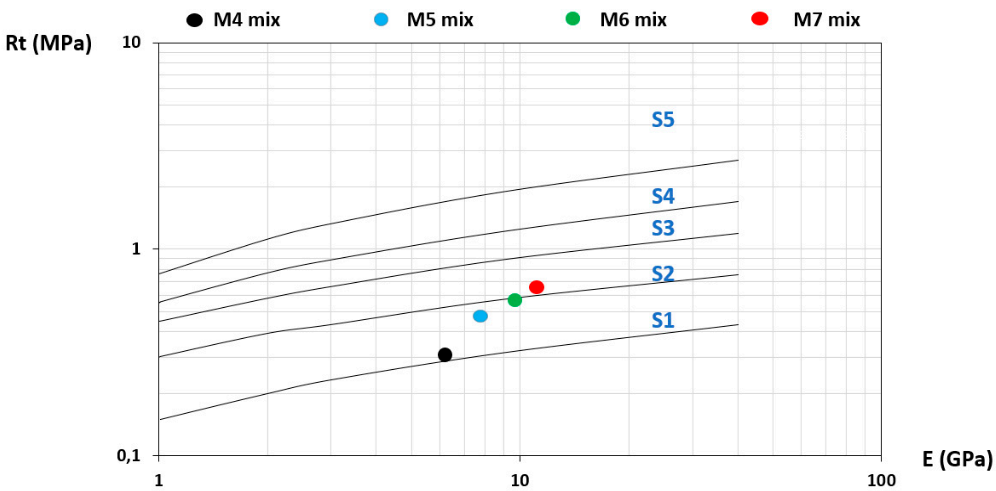

Figure 9. Structural classification of designed mixes according to NF-P98-113 [38].

3.3. Preliminary Economic Evaluation

The objective of this preliminary economic investigation is to determine the radius (around the Jerada city) profitability beyond which the CMWR will no longer be competitive given the average prices of embankments made with conventional materials. In this study, the calculation of the overall cost for CMWR embankment use generally requires taking into account the investment costs (COPEX) and that of maintenance (OPEX) during the service life. The evaluation consists of analysing the main costs related to the scenario based on using CMWR in the construction of road embankments and to compare them with that of the conventional materials. Because maintenance and operating costs are assumed to be almost the same, the approach will focus only on the construction costs life cycle (Capital expenditures, CAPEX). The road embankment under a wet mixing process includes extraction, loading, transportation, unloading, and implementation of materials. However, the most important parameter affecting the overall costs is that of transport and, therefore, the distance from the supply resources to the destination. Using a 15 m^3 truck capacity in normal conditions, the calculation of the total cost of transport requires taking into consideration the variable and the fixed costs. Table 8 lists the different these costs for transporting road materials and the fundamental assumptions underlying the calculation of the profitability radius.

Table 8. Variable and fixed costs for transporting road materials.

Variables Costs	Fixed Costs
• Raw materials (fuel) • Vehicle maintenance (emptying, repair, washing...) • Tires wear	• Driver (salary, travel expenses...) • Vehicle (cost related to financing, depreciation, taxes, insurance, technical visits...) • Operating costs (administrative costs, taxes...)
Assumptions	
• Operating costs by a medium-sized company (road works) • Vehicle maintenance (oil change...) every 10,000 km (as average) • Changing a set of tires each 40,000 km (as average) • The average consumption of a 15 m^3 load truck on a flat to the hilly area is taken equal to 48 litres/100 km • The calculation of the annual distance travelled assumes that an average of 240 km/day	

The average prices per year in Morocco of different services planned for the execution of road embankment are illustrated in Table 9. The various financial costs and prices mentioned below are taken from a survey carried out between January 2018 and January 2019 from a dozen companies in the oriental region specializing in road construction.

Table 10 gives a comparison study based on the details of the costs of foreseen tasks for the realization of embankments with CMWR and conventional materials. The radius of profitability (R) can be determined according to the following equation (Equation (4)):

$$(((P + R.I).Coeff(exp)) + \Sigma\ (\text{other prices})).Pro = Sp \quad (4)$$

where P is the purchase of materials; R is the radius of profitability; T is the cost of transport; *Coeff (exp)* is expansion coefficient; other prices are the price of implementation + extraction+ loading and rehabilitation of the extraction zone; *Pro* is profit margin and *Sp* is the sale price.

Based on the reported results in Table 10 and Equation (4), the CMWR materials can be used as embankment materials in a radius of 29 km around the Jerada mine, unlike conventional materials that lose their profitability beyond 10 km. The calculation was done assuming that conventional resources are available, otherwise, this radius of profitability will have to correct downward.

Table 9. Annual costs related to the various services provided for the execution of an embankment.

Designation	Costs (€)
Depreciation expense	2900
Expenses driving staff	7800
Insurance fees	1160
Dues and taxes	1015
Total Fixed Fees (€)	**12,895**
Fuel and lubricant	33,002
Pneumatic	2400
Maintenance and repair	2450
Total Variables Fees (€)	**37,852**
Operating costs	2500
Other	1000
Total structure fees (€)	**3500**
Total return price (€)	**54,247**
Average distance travelled per year (km)	**7488**
Cost price per kilometre rolled (€)	**0.72**
Cost price per m^3 kilometre (€)	**0.048**

Table 10. Calculation of the radius of profitability.

(Average Costs Excluding Taxes)	Unit	CMWR Materials	Conventional Materials
Cost of transport	€.m^3/km	0.048	0.048
Expansion coefficient		1.15	1.15
Profit margin	%	15	15
Loading cost	€	0.30	0.30
Cost of implementation	€	0.85	0.80
Extraction cost	€	0.10	0.30
Purchase of materials	€	0.10	0.70
Cost of rehabilitation of the extraction zones	€	0.10	0.30
The sale price of road embankment	€	3.5	3.5
The radius of profitability (R)	km	29	10

4. Conclusions

The feasibility of using coal mine waste rocks locally in road construction was assessed. After deep characterizations of raw materials at the laboratory scale, a new method to recycle coal mine waste rocks and abandoned fly ashes of Jerada city (Morocco) for road pavement application by using a solidification process was provided. The laboratory study has revealed that the use of CMWR alone should be limited to ordinary embankments outside of flood zones, engineering structures, and the top part of the earthworks. Furthermore, the high granulometric evolution observed under mechanical stress and the CBR (4i) strength results allowed us to conclude that the modified energy of the Proctor test is more appropriate for embankment compaction of CMWR materials. Due to their sensitivity to water and their low resistance to degradation by abrasion and wear, the CMWR aggregates were unable alone to meet the pavement material specifications. The laboratory investigations of the mechanical performances proved the ability of the CMWR:FA:HRB = 80:20:5 mix to be used as a foundation and as a base-course material. From an environmental point of view, the concentrations of leached metals from ground CMWR was under the limit requirements fixed by the US-EPA regulation. Furthermore, the environmental impact of acid mine drainage associated with pyritic waste can be neglected.

Based on the economic case study, the CMWR can be utilized as embankment aggregates in a radius of 29 km around the Jerada mine keeping a lower cost compared to conventional materials.

To examine the CMWR pavement structure under real conditions (evolutionary behaviour in terms of grain size distribution and *MBV* properties, bearing capacity) and to verify the target densification objective for the road embankment construction, field investigations are required. Further research is needed to confirm the predictive elastic modulus of this new material. The collaboration between different concerned actors such as the thermal power plants of Jerada and stakeholder engagement is highly recommended to encourage the use of both CMWR and FA by-products. This manner of doing will lead to various benefits such as air emission reduction, and finite natural resources conservation.

Author Contributions: M.A.: Conceptualization, Validation, Writing—Original Draft. Y.T.: Investigation, Supervision, Review and Editing. Y.E.H.: Validation, Writing—Review and Editing. M.B.: Formal analysis, Review and Editing Supervision. R.H.: Supervision, Methodology. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported through the International Research Chairs Initiative, a program funded by the International Development Research Centre, Canada (IDRC), and supported by the Canadian Research Chairs Program.

Conflicts of Interest: The authors declare no conflict of interest.

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