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Potential valorisation of steel slag waste as an alternative material for pavement layers

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Research Paper

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Potential valorisation of steel slag waste as an alternative material for pavement layers

This paper aims to investigate the feasibility of using steel slag waste as an alternative material for pavement layers (sub-base and base layers). This waste is stored and landfilled at a steel production site in JORF LASFAR, city of El Jadida, Morocco. Samples of the waste were collected and underwent standard tests to determine its physical, chemical, mineralogical, and geotechnical properties. Furthermore, the steel slag waste cannot be used alone in pavement layers because of the low fraction of fine aggregates. Additionally, a sterile raw material (rock crushing waste) was used with the steel slag waste to obtain the required particle size distribution. Five mixtures of steel slag (SS) and sterile (ST) were formulated using the following proportions (% SS: % ST): M1 (30:70), M2 (40:60), M3 (50:50), M4 (60:40), and M5 (70:30). Geotechnical and mechanical standard tests were conducted on each mixture, including the M4 and M5 mixtures, to determine whether they met the required properties for a material used in the base layer. M2 to M5 mixtures also had the necessary properties for the sub-base layer. Finally, a sizing study was performed to obtain the thickness of pavement layers containing the formulated mixtures, which were found to be close to those of conventional materials.

Key words:

steel slag, valorisation, road technology, base course, mechanical performance

Prethodno priopćenje

Lahcen Es-Samlali, Yassine EL Haloui, Mustapha Amrani, Fahd Oudrhiri-Hassani, Abdelmonaim Tlidi, Abdderahman Bekri

Potencijalna valorizacija otpadne čelične zgure kao alternativnog materijala za kolničke slojeve

Cilj ovog rada istražiti izvedivost korištenja otpadne čelične zgure kao zamjenskog materijala za slojeve kolničke konstrukcije (nosive slojeve). Ovaj se otpad skladišti i odlaže na odlagalište na lokaciji za proizvodnju čelika u JORF LASFAR-u, u gradu El Jadida, Maroko. Prikupljeni su uzorci otpada koji su podvrgnuti standardnim ispitivanjima kako bi se utvrdila njihova fizikalna, kemijska, mineraloška i geotehnička svojstva. Nadalje, otpadna čelična zgura ne može se koristiti samostalno u slojevima kolničke konstrukcije zbog niskog udjela sitnog agregata. Prirodni materijal (otpad od drobljenja kamena) upotrijebljen je s otpadnom čeličnom zgurom kako bi se postigla zahtijevana granulometrijska krivulja. Napravljeno je ukupno pet različitih mješavina čelične zgure (SS) i prirodnog agregata (ST) u sljedećim omjerima (% SS: % ST): M1 (30:70), M2 (40:60), M3 (50:50), M4 (60:40), i M5 (70:30). Provedena su geotehnička i mehanička ispitivanja svake pojedinačne mješavine, uključujući i mješavine M4 i M5, kako bi se utvrdilo ispunjavaju li te mješavine uvjete da bi se koristile u gornjim nosivim slojevima. Mješavine oznaka od M2 do M5 također su imale svojstva koja su potrebna za materijal donjih nosivih slojeva. Na kraju je provedena analiza dimenzioniranja kolničke konstrukcije kako bi se dobila debljina slojeva koji sadrže formulirane mješavine, za koje je utvrđeno da su slične debljinama konvencionalnih materijala.

Ključne riječi:
čelična zgura, valorizacija, tehnologija izgradnje cesta, nosivi sloj, mehanička svojstva

1. Introduction

1.1. Steal slag production

Steel slag waste is a by-product of steelmaking produced during the separation step of the molten steel from impurities in steel-making furnaces. The slag occurs as a molten liquid and is a complex solution of oxides and silicates that solidifies upon cooling [1]. Co-products are classified into two groups: basic oxygen furnaces (BOF) and electric arc furnaces (EAF) [2]. A high-pressure oxygen lance is injected into the furnace containing hot liquid metal from blast furnaces during the BOF process, consisting of lime and dolomitic lime. Oxygen removes impurities from the charge [1]. These impurities are composed of carbon in forms of gaseous carbon monoxide of silicon, manganese, phosphorus, and iron in the form of liquid oxides, which are combined with lime and dolomitic lime to form steel slag [1]. According to Rees [3], the EAF uses cold scrap steel, pig iron, and direct reduction iron. An electric arc is introduced to obtain sufficient heat to melt the scrap. An electric current passes through the three graphite electrodes to form this arc. During the smelting process, other minerals (ferrous alloys) are added to the steel to give it the required chemical composition. Furthermore, oxygen is also injected to purify the steel. In the end, the floating steel slag is separated from the surface of the molten steel (c). The general steps of steel slag production are shown in Figure 1.

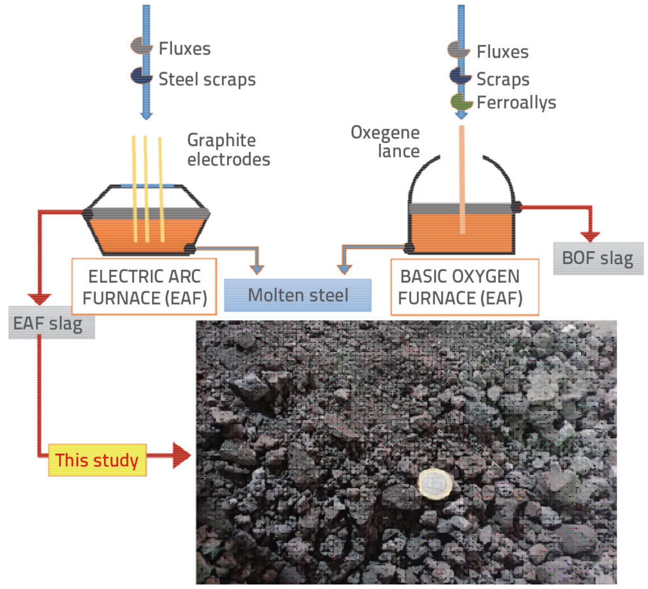

Figure 1. Schematic of basic oxygen furnace and electric arc furnace

According to Barra [4], producing three tonnes of stainless steel generates approximately one tonne of steel slag (SS). Therefore, a huge quantity of waste is frequently generated for the steel industry. Additionally, steel industries all over the world generate fifty million tonnes of steel slag waste each year. In Europe alone, approximately twelve million tons of steel slag waste are produced per year [5]. The steel industry generates approximately 115,000 tonnes of steel slag per year in Morocco. This waste is generally stored in dumps or stockpiles designed for that purpose at or near the manufacturing sites. However, this storage negatively impacts the environment and poses health risks to humans. In addition, the restoration of these dams and accumulation zones is very expensive.

1.2 Literature analysis

The valorisation of wastes in civil engineering has become an efficient way to manage them and reduce their impacts on environmental and human health [6-8]. The reuse and recycling of steel slag waste in the civil engineering field is an interesting option for its management. Furthermore, many studies have been conducted to demonstrate the potential reuse of this waste. These studies were conducted for different sectors of civil engineering, including soil, cement, concrete, and pavement. Aziz et al. [9] showed that steel slags offer ideal durability, permeability, stability, and resistance against abrasion, cracking, and permanent deformation in soil applications. Therefore, steel slags could provide physical and mechanical properties equal to or better than natural aggregates. Despite the volume instability and high specific gravity of steel slag, they possess favourable properties such as self-carburizing and a high friction angle to stabilise and strengthen soils. Isaac Akinwumi showed that adding 8 % of the pulverised steel slag to the lateral soil improves the unhardened strength of the soil to ensure that its unhardened CBR increases by 40 %, and its unconfined compressive strength is 66.7 kN/m^2. Furthermore, the liquid and plastic limits, as well as the plasticity index, were reduced by 6.3, 4.0 and 2.3 %, respectively, exploiting the pozzolanic reactions and superior mechanical properties of EAF slag results significantly in the strength of the stabilized soil to reduce the cost by reducing the demand of cement [10]. Shahbazi et al. [11] showed that the use of 16 % steel slag and carpet waste fibres as additives decreased the swelling rate and improved the mechanical properties of the expansive soil. Wang et al. [12] illustrated that the rate of immersion resistance of soil stabilised by steel slag increased with increasing compaction degree and steel slag content. Abdalqadir and Salih [13] indicated that the addition of 10 % to 20 % steel slag and 10 to 15 % crushed limestone improved the geotechnical properties of expansive soils. Cikmit et al. [14] investigated the expansion of steel slag mixed with soft marine clay and determined that the addition of 60 % steel slag allowed heavy geomaterial while conforming to allowable expansion.

Zhang et al. showed that the compressive strength of the composite cement containing 40 % steel slag is comparable to 42.5R cement in cement applications [15]. According to the study of Gao et al. [16], the use of steel slag for the production of clinkers indicated that the maximum amount of steel slag that can be added to raw meal is 14.30 %. Xiang et al. [17] presented a method of using steel slag (without grinding it into a fine powder) to prepare cement-less cementitious material for the compressive strength of mortar to reach 70 MPa.

Steel slags were used as an alternative aggregate in concrete mixtures for construction applications. An ultra-high-performance concrete composed of steel slag powder and steel slag aggregate produced satisfactory compressive strengths with a cement replacement rate of less than 10 [18]. Furthermore, the use of residual steel slag in concrete as a replacement for conventional coarse aggregates demonstrated that slag aggregates offer a significant improvement in compression strength of 18 % at seven days and 16.8 % at 28 days compared to conventional concrete [19]. According to Wang et al. [20], the use of 100% steel slag in concrete improves its tensile compressive and breaking strengths, increasing them by 35 % and 50 %, respectively. According to Shen et al. [21], the permeable concrete of the carbonated steel slag saved 75.8% in material cost because it was 100 % solid waste and absorbed about 100 kg / m^3 of CO2, which was found to be an environmentally friendly approach.

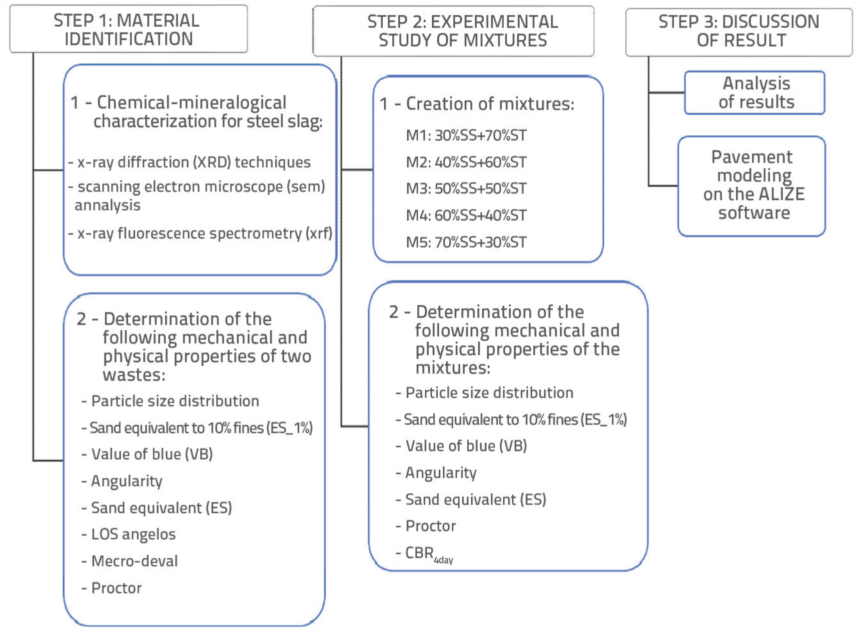

Figure 2. General steps of the study

Maghool et al. conducted a series of characterization tests to evaluate the engineering properties of steel slag for use as a base material for pavements, the results of which indicate that the engineering properties of steel slag are close to or even superior to those of typical quarry materials [22]. Gao et al. [23] showed a high feasibility of steel slag reuse in asphalt mixtures to melt ice by microwave, which is useful for alleviating the shortage of natural aggregate supply and improving road traffic safety in winter. The pavement course layer with steel slag also showed excellent performance on roughness and the British Pendulum Number surface coefficient [24]. According to Kim et al. [25], the behaviour of a hot bituminous mixture containing steel slag aggregates was improved in terms of dynamic modulus and resistance to rutting. Dondi et al. [26] demonstrated that the use of steel slag is efficient for the construction of the entire pavement structure, either in the cement layers or in the bituminous conglomerate. The use of an optimal mixture of 4.5 % bitumen and 30 % slag increases the rigidity of the mixes.

1.3. Scope of the study

The literature review showed that very few studies have been conducted on the direct reuse potential of steel slag waste in road bases and sub-base embankments. In addition, such waste steel slag has its own special features, Therefore, it should be characterized. Therefore, this study assesses the sustainable use of steel slag as an alternative material for road construction. We investigated the potential of using this waste in the base and sub-base layers of roads. Step 1 of this study is conducted by performing chemical and mineralogical characterizations of steel slag. In Step 2, we discuss the physical and mechanical characterizations of five mixtures of materials containing steel slag waste mixed with sterile material (ST) (waste from quarry crushers that produce road construction materials). Step 3 discusses the results regarding the sustainable use of steel slag. Figure 2 summarises the general steps of the study.

2. Materials and methods

2.1. Raw materials

In this study, two types of waste were considered. The first type is presented in Figure 3a. It is industrial steel slag waste collected

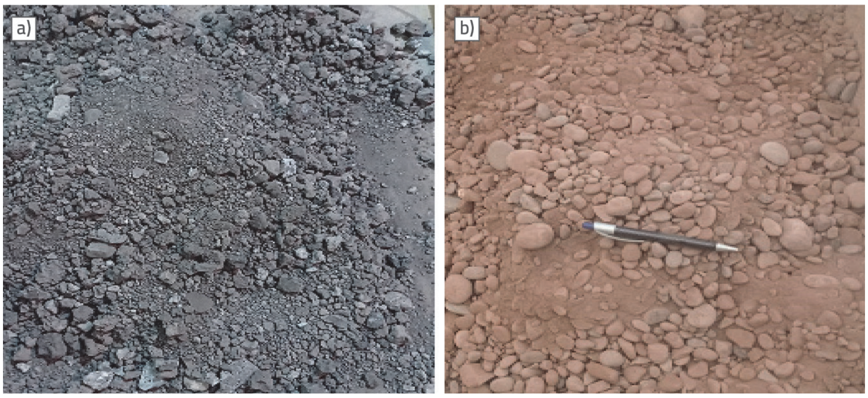

Figure 3. Raw materials: a) Steal slag (SS); b) Sterile (ST)

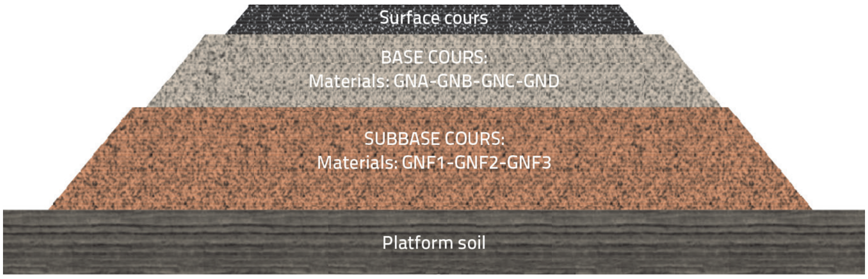

Figure 4. Example of a pavement structure

from the Eljorf Sfar landfill, located in region of the El Jadida, Morocco. Large quantities of slag from the Eljorf Sfar steelworks were buried in a large area during a long period of steel production by recycling scrap metal. The second type of waste is sterile and is shown in Figure 3b. It is produced during the process of manufacturing road material by crushing rocks from rivers. During this process of crushing, screening occurs to eliminate the fine elements of dust and unnecessary elements that produce waste. The latter are the waste rocks (ST) that have been collected by the quarries in the same area.

2.2. Test methods

We used X-ray diffraction (XRD), scanning electron microscope (SEM) analysis, and X-ray fluorescence spectrometry (XRF) for chemical and mineralogical characterizations of SS. Samples of each type of material were taken from different points of the storage site. Furthermore, the material was mixed for each type, homogenized, and divided into smaller sub-samples before being tested in the laboratory. We carried out a series of tests in the laboratory to determine the physical and mechanical characteristics of SS and ST. A pycnometer method was used to determine the actual densities according to the NF EN 1097-6 standard [27]. The particle size distribution was conducted on samples by dry sieving for an element with a diameter greater than 80 μm according to the NF EN 933-1 standard [28]. The plasticity index (PI) of samples was measured using the Atterberg limit test according to the NF EN ISO 17892-12 standard [29]. The sand equivalent test was conducted based on the specification of P18-598 standards to measure the cleanliness of the sand and get a general idea of the quantity and quality of fine elements [30]. The Proctor test was performed on the fraction 0/200 mm according to the NF P94-093 standard to determine the optimal water content and the maximum dry density. A dial gauge and CBR mould (after 15 days of immersion in water) were used to quantify the swelling of samples. In addition, a CBR test was performed to determine the load bearing capacity of a material under conditions of compaction and optimum water content, according to NF P 94-078 standard [32]. The resistance of aggregate to fragmentation was determined based on the Los Angeles test in accordance with the NF P 18-573 standard [33]. The aggregate resistance to wear was measured by the Micro-Deval test according to the NF P18-572 standard [34].

2.3. Target materials

The flexible pavement structure is the most used variant of pavement in Morocco. Additionally, this structure consists of surface, base, and sub-base courses, as shown in figure 4. In this study, the target materials used to substitute the steel slag waste are untreated gravel materials. The base courses are built using GNA, GNB, GNC, and GND types of untreated gravel. The gravel considered untreated is GNF1, GNF2, and GNF3 for sub-base courses. The selection of this type of untreated gravel for a course is based on pavement sizing. Each material is characterised by many specific

Table 1. Required characteristics of untreated gravel materials for pavement layers

Material	Mechanical properties [%]	Angularity, I_c [%]	Cleanliness	Passing percentage [%]							
				60	40	31.5	20	10	6.3	2	0.08
GNA	LA < 30; MDE < 20	$I_c > 100$	ES(0/5) > 30 ES(0/2) > 45 VB < 1.5	-	100	85 to 100	62 to 90	35 to 62	25 to 50	14 to 34	2 to 10
GNB	LA < 30; MDE < 20	$I_c > 35$									
GNC	LA < 35; MDE < 30	$I_c > 30$	VB < 1.5 IP < 12		100	-	52 to 87	35 to 70	25 to 60	13 to 38	2 to 10
GND	LA < 40; MDE < 35	admissible roll									
GNF1	LA < 30; MDE < 25	$I_c > 60$	ES(0/5) > 30 IP < 6 VB < 1.5	-	100	-	60 to 90	40 to 70	33 to 64	20 to 48	2 to 14
GNF2	LA < 40; MDE < 35	$I_c > 30$	IP < 8	100	80 to 100	-	47 to 90	30 to 70	20 to 64	10 to 48	2 to 14
GNF3	LA < 50; MDE < 45	unconditionally									

properties, including grading size of aggregates, angularity, cleanliness, bearing capacity, mechanical resistance, etc. The properties of each target material are listed in Table 1. Furthermore, the objective of this study is to determine the aforementioned properties of several designed mixtures of SS and ST wastes (seven mixes) and then discover the mixes that can substitute untreated gravel (GNA-B-C-D and GNF1-2-3).

3. Results and discussion

3.1. Characterization of steal slag and sterile

The first part of raw material characterization focuses on the determination of the geotechnical properties of SS and ST. Additionally, the specific gravity was measured and found to be approximately 3.26 T/m^3, which is close to that of untreated gravel material. The particle size distribution test was conducted for both materials, and the results are illustrated in Figure 5.

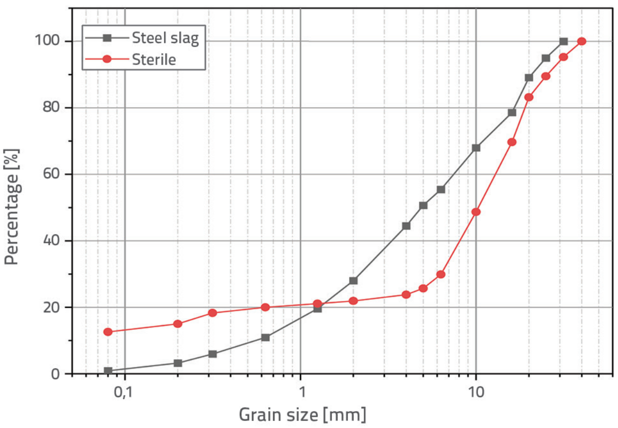

Figure 5. Grain size of steel slag (SS) and sterile (ST)

The main properties are listed in Table 2. Furthermore, the fines in the steel slag waste were low (Passers-by to 0.08 mm less than 1 %). In addition, the uniformity coefficient was higher than two and the curvature coefficient was less than one. Therefore, the SS material was well graded and continued. The plasticity of the steel slag was not measurable. Therefore, the VB test was conducted to characterise the soil as having low plasticity. The discovered VB was 0.045 g/100g. Moreover, this cleanliness of the steel slag amounted to their poverty in fines, therefore resulting in the steel slag's insensitivity to water. The values of the Los Angeles and MDE coefficients are 11 and 8 %, respectively, which indicates that the steel slag is a very rigid material for mechanical performance. The modified proctor test for steal slag results in non-cohesive material because of a lack of fines. Therefore, it is necessary to add such material (the reason for using sterile material) to slag waste to ensure good compaction [35]. The swelling determination was made by one-month CBR testing and showed that no change in volume was observed, indicating that the sample taken had an ageing period. Laboratory tests on the sterile showed that the grain size is rich in fine particles below 0.08 mm; the passage to 0.08 mm is 12.6 %; and the particle size fraction from 2 mm to 5 mm has a low percentage of approximately 5 %, as shown in Table 2. The VB index was 3.9, which showed that the sterile was not very clean but exceeded the local requirements. The sterile aggregates have better resistance to fragmentation and wear. Therefore, the LA and MDE values were 18 % and 13 %, respectively.

Table 2. Geotechnical and mechanical properties of steel slag and sterile

Test	**Steel slag**	**Sterile**
Specific gravity	3.26	2.47
Cu (coefficient of uniformity)	12.7	---
Cc (coefficient of curvature)	0.96	---
Passers-by to 0.08 mm [%]	0.9	12.6
Passers-by to 2 mm [%]	28	22
Passers-by to 5 mm [%]	54	26
Passers-by to 31.5 mm [%]	100	97
Angularity [%]	100	20
Sand equivalent [%]	79	22
VB [g/100g]	0.045	3.9
OMC (*Optimum moisture content*) [%]	4.2	10.9
MDD (*Maximum dry density Immediate*) [g/cm^3]	2.44	2.01
LA [%]	11	18
MDE (*Micro Deval coefficient*) [%]	8	13
Swelling [%]	<1	---

According to the geotechnical results of steel slag and sterile based on the Moroccan Guide to Soil Classification (GMTR), the steel slag can be classified as a D2 type water-insensitive soil, and the sterile is a B6 type clay-gravel soil, as shown in Figure 6.

Regarding the slag morphology, the slag had irregular shapes with sharp edges and low sphericity varying from sub-rounded to sub-angular, as shown in Figure 7. A SEM Scanning Electron Microscopy technology was used to study the silt-sized slag particles. Therefore, they have a very coarse surface texture and a porous structure.

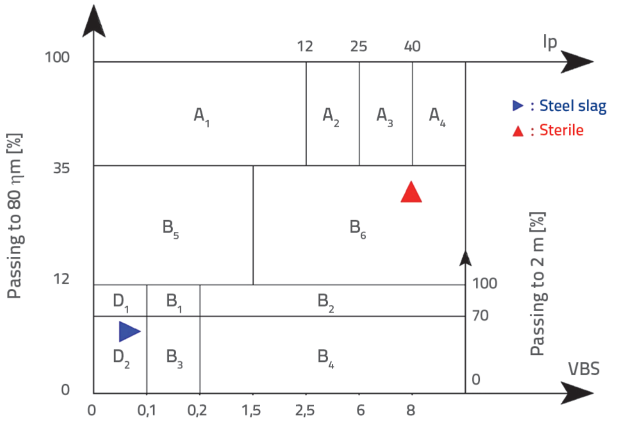

Figure 6. Steel slag classification based on GMTR guide

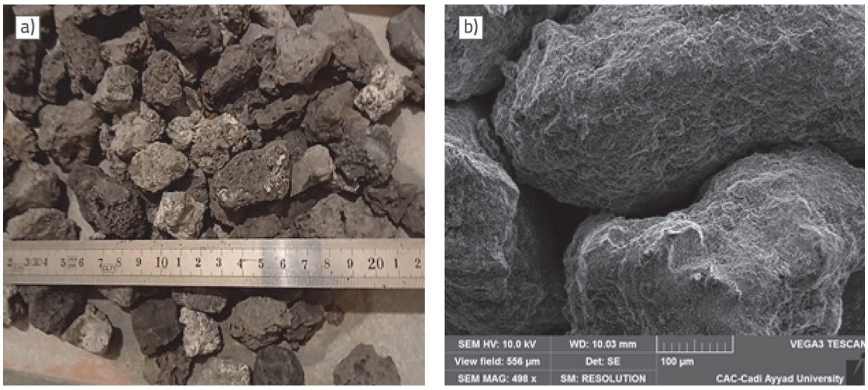

Figure 7. a) Coarse-grained morphology of steel slag; b) SEM micrograph showing the surface texture of a silt-sized steel slag particle (500X)

The mineralogical analysis was performed on the steel slag powder by using RDX diffraction. The obtained results are shown in Figure 8. The diffraction patterns show a highly crystalline nature; the predominant metallic phases in the steel slag are: Silicon and iron oxide Fe2.95Si0.05O4, Calcium Silicate: $CaSiO_3$, Calcium Carbonate: $CaCO_3$, Magnesium Oxide MgO, Calcium Iron Aluminium Oxide: Ca_2FeAlO_5, Calcium Aluminium Silicate: $Ca_2Al(AlSi)O_7$, Calcium Magnesium Silicate: Ca3Mg(SiO4)2, Calcium Silicate: Ca_2SiO_4. These results are consistent with those of studies conducted in the literature, such as the Tsakiridis et al. study and the Barra et al. study [4, 27].

Analiza kemijskog sastava čelične zgure provedena je The X-ray fluorescence spectrometry was used to perform the chemical analysis of steal slag. The chemical elements are listed in Table 3. The oxides CaO, SiO_2, Fe_2O_3, Al_2O_3, MgO, and FeO represent most of the chemical constituents of the steel slag. Furthermore, the chemical properties of steel slag are highly dependent on the quantities of oxides in the raw materials used (cast iron, scrap metal, etc.), chemicals or compounds added during the manufacturing process [37].

Regarding the mineralogical composition (Table 4), calcium carbonate (CaCO3) and silicate (Ca2SiO4) are the major crystalline mineral phases contained in steel slag (wt.%= 62.7 %). In addition, iron silicon oxide and calcium aluminium silicate represent approximately 20 %. Low proportions of Merwinite, Brownmillerite, and Periclase were also detected.

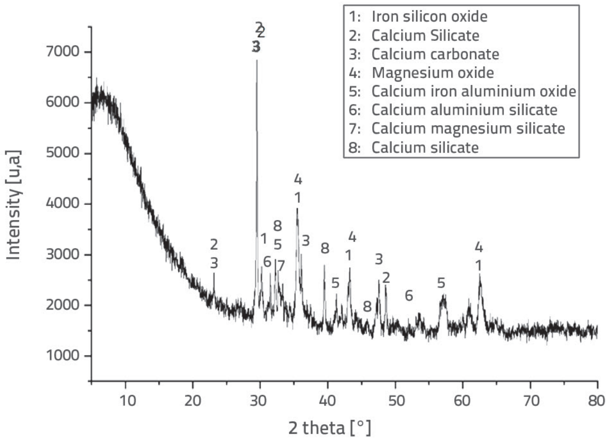

Figure 8. RDX diffraction patterns of steel slag

3.2. Design of mixtures

The steel slag waste contains a low quantity of fine particles (passers-by to 0.08 mm are less than 1 %). Therefore, the particle size curve of the slag does not respect the required limits of the target materials, as shown in Figure 9. Because the target materials have generally between two to 14 % of fine particles, the grain size of steel slag must be corrected by adding another material that contains fine particles. Therefore, the selected material was sterile waste, and its grain size curve is illustrated also in Figure 9.

A theoretical composition study was conducted to determine the ratios of the two waste materials to make mixtures that verify the required limits regarding grain size distribution, as shown in Figure 9. Furthermore, five mixtures were designed: M1 to M5. The details of the mixtures are listed in Table 5. The theoretical

Table 3. Chemical composition of steel slag

Oxides	Al_2O_3	MgO	SiO_2	P_2O_5	Na_2O	KO_2	CaO	TiO_2	SO_3	MnO	Fe_2O_3	LOI
Chemical composition [%]	7.59	4.15	15.31	0.45	1.05	0.05	29.31	0.60	1.76	3.78	31.23	2.70

Table 4. Mineralogical composition of steal slag

Mineralogical element	Chemical formula	Weight fraction [%]
Calcium carbonate	$CaCO_3$	41.2
Calcium silicate (larnite)	Ca_2SiO_4	21.5
Iron silicon oxide	$Fe_2.95\ Si0.05\ O_4$	10.8
Calcium aluminium silicate (gehlenite)	$Ca2\ (Al(Al\ Si)\ O_7)$	9.4
Calcium silicate (wollastonite)	$Ca\ Si\ O_3$	6.2
Calcium magnesium silicate (merwinite)	$Ca_3\ Mg\ (SiO4)_2$	4.5
Calcium Iron aluminum oxide (brownmillerite)	Ca_2FeAlO_5	4.5
Magnesium oxide (periclase)	MgO	2

grain size curves of these mixtures are shown in Figure 10. The grain size curves of all mixtures are between those of the target materials. Additionally, experimental tests were conducted on all mixtures to confirm the results of the theoretical study.

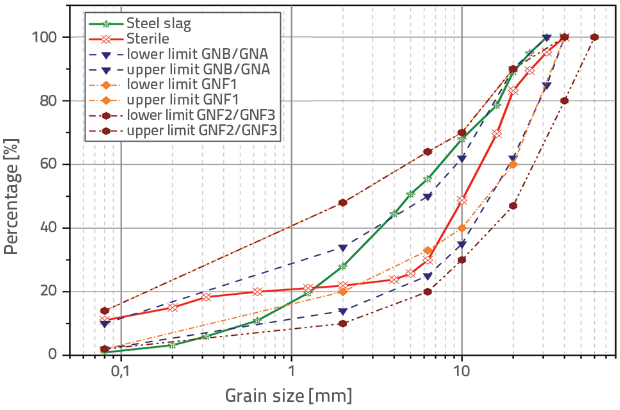

Figure 9. Grain size distribution of steel slag (SS), sterile (ST) and the required limits of target materials

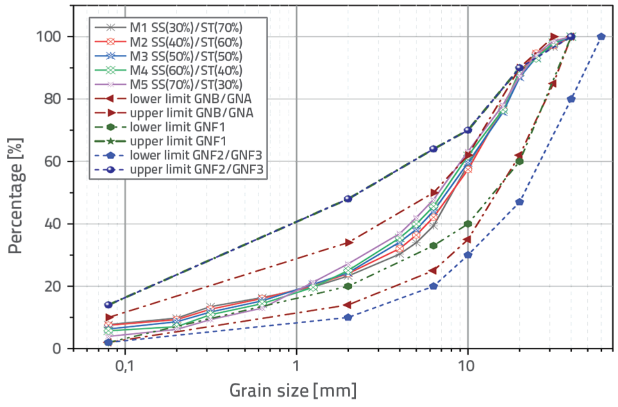

Figure 10. Particle size distribution of the mixtures

3.3. Technical properties of designed mixtures

The designed mixtures (M1 to M5) were subjected to a series of tests to evaluate their mechanical and geotechnical properties, such as the particle size analysis, sand equivalence, methylene blue value, Proctor, and CBR tests. The obtained results are shown in Table 6. Furthermore, the replacement of steel slag with sterile has been affected by all technical properties. Additionally, the addition of sterile to the mixtures leads to an increase in the proportion of fines (aggregates lower than 0.08 mm), which results in particle size distributions in agreement with the standards. The methylene blue value of the mixes was decreased from 2.7 for the M1 mix to 0.7 for the M5 mix, and thus the sand equivalent value of the mixes was increased from 24.3 % for the M1 mix to 63.9 % for the M5 mix. Therefore, the increase in the steel slag content has a positive effect on the cleanliness of the mixes. Regarding the Proctor test, the dry density of the mixes depends on the slag content to vary the densities from 2.28 for M1 to 2.41 for M5. This variation of the maximum dry density can be explained by the high specific gravity of the steel slag compared to that of the sterile. In addition, the optimal water content was decreased from 6.3% to 4.3 % because of the filling of pores on the surface of the slag. The CBR value at four days of immersion was added with the slag content to ensure that values vary from 58 % to 156 %. Furthermore, the bearing capacity of the mixes was improved because of the high angularity and cementitious aspect of the steel slag. The addition of 30 to 70 % of steel slag proportion with sterile in the mixtures improved the steal slag grading defects to obtain a suitable material for use in the pavement base and sub-base layers. Additionally, the variations in the technical properties (VB, OMC, MDD, and CBR) of mixtures are shown in Fig 11. A fitting analysis was conducted to obtain a fitting equation for each property.

Table 5. Proportions of each waste for the mixtures

Mix	M1	M2	M3	M4	M5
Percentage of steal slag waste	30	40	50	60	70
Percentage of sterile waste	70	60	50	40	30

Table 6. Technical properties of mixtures M1, M2, M3, M4, and M5

Property	M1	M2	M3	M4	M5
Passers-by at 0.08 mm [%]	7.7	7.5	6.3	5.7	3.9
Passers-by at 2 mm [%]	23.3	24.1	24.3	25.1	27.2
Passers-by at 5 mm [%]	34.0	36.4	38.2	39.9	42.0
Passers-by at 20 mm [%]	89.1	88.6	87.0	88.8	87.4
Angularity, Ic [%]	45.4	51.2	57.5	66.8	75.1
Sand equivalent [%]	24.3	32.8	41.3	54.1	63.9
VB (g/100g) [%]	2.6	1.82	1.45	1.09	0.7
OMC [%]	6.3	5.9	5.2	4.6	4.3
MDD [g/cm^3]	2.28	2.32	2.34	2.37	2.41
IPI [%]	29	38	49	57	79
CBR, after 4 days [%]	58	77	93	110	156

3.4. Evaluation of designed mixes for road pavement use

In this section, the technical properties of the designed mixes M1 to M5 were evaluated to investigate the feasibility of incorporating them in road pavement and sub-base course layers. The potential use of these wastes in course layers requires the verification of many conditions concerning the required characteristics of materials that are presented in Table 1. In addition, a crucial condition concerning the CBR value must be considered to make an informed decision regarding the reuse of these wastes in road. Furthermore, the CBR index must be greater than 100 % for a base course material and 60 % for a sub-base course material [38]. Furthermore, the French guide requires that the following immediate stability conditions be met: IBI > 50 for the base course, and IBI > 35 for the subbase course [39]. Based on the finding results of CBR and IPI (see Table 6), the mixture M1 cannot be used as an alternative material either for base and sub-base course layers because its CBR is low than 60 % (58 % for M1). The found values of CBR are higher than 60 % (77 % and 93 % for M2 and M3, respectively) and can be used for sub-base courses. However, they are not recommended to be used for the base course layer (CBR values are less than 100 %). M4 and M5 mixtures can be used as alternative materials for the base and sub-base course layers. In summary, M2, M3, M4, and M5 mixes are recommended as alternative materials for sub-base layers. Moreover, M4 and M5 mixes are recommended as alternative materials for base layer. The mixes verifying the CBR condition must also justify the required characteristics (mechanical resistance, cleanliness, angularity, and particle size), as shown in Table 1. GNA, GNB, GNC and GND and GNF1, GNF2 and GNF3 are the conventional materials used in Morocco for base and sub-base course layers, respectively. Therefore, the findings in Table 6 reveal that each technical property of each mixture was compared with the required characteristic value to establish Tables 7 and 8.

Table 7. Potential use of M4 and M5 mixes as alternative base course materials.

Property	**Mechanical resistance**		**Cleanliness**	
	Verified (V) or not (NV)			
Material	M4	M5	M4	M5
GNA	V	V	V	V
GNB	V	V	V	V
GNC	V	V	V	V
GND	V	V	V	V
Property	**Angularity**		**Size particles**	
	Verified (V) or not (NV)			
Material	M4	M5	M4	M5
GNA	NV	NV	V	V
GNB	V	V	V	V
GNC	V	V	V	V
GND	V	V	V	V

The potential use of the mixes as base course materials (for GNA, GNB, GNC ans GND replacement) revealed that M4 and M5 satisfied all the required characteristics except the angularity of GNA material. Furthermore, adding sterile (low angularity) to steel slag (high angularity) decreases the global angularity of the mixture. Either M4 or M5 cannot be used as GNA because the material must present a high angularity (Ic > 100 %). Therefore, M4 and M5 are recommended as alternative GNB, GNC, and GND materials.

The possible use of the mixes as sub-base course materials as M2 mix does not satisfy the cleanliness properties of GNF1 and GNF2, as well as the angularity of GNF1. In addition, M3 does not fulfil the angularity of GNF1.

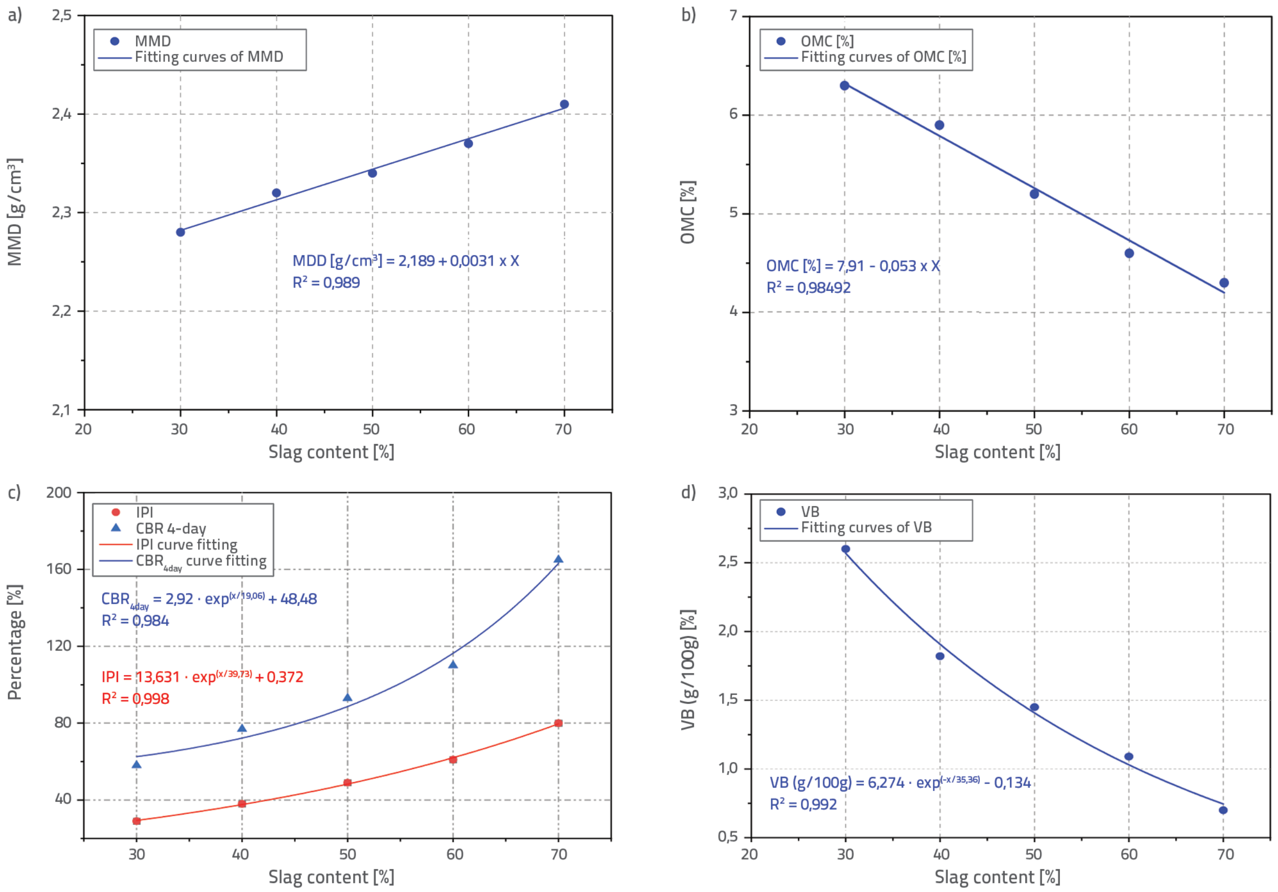

Figure 11. Fitting of technical properties of all mixtures: a) for MMD; b) for OMC; c) for CBR and IPI; d) for VB

Table 8. Potential use of mixtures as alternative sub-base course material

Property	**Mechanical resistance**				**Cleanliness**			
	Verified (V) or not verified (NV)							
Material	M2	M3	M4	M5	M2	M3	M4	M5
GNF1	V	V	V	V	NV	V	V	V
GNF2	V	V	V	V	NV	V	V	V
GNF3	V	V	V	V	V	V	V	V
Property	**Angularity**				**Size particles**			
	Verified (V) or not verified (NV)							
Material	M2	M3	M4	M5	M2	M3	M4	M5
GNF1	NV	NV	V	V	V	V	V	V
GNF2	V	V	V	V	V	V	V	V
GNF3	V	V	V	V	V	V	V	V

Therefore, it is recommended to use M2 mix as GNF3, M3 mix as GNF2 and GNF3.

Finally, M4 and M5 mixes can be used for all sub-base course materials (GNF1-2-3).

3.5. Pavement design with the formulated mixtures

In this section, an attempt at pavement design is conducted using the designed mixtures of waste as materials for the base

Table 9. Literature equation used to estimate the modulus of elasticity.

Name	Fields of utilization	Equation	Reference
Green and Hall (1975) (US Army Corps of Engineers)	Base, Subbase and Subgrade Materials	$E = 37 \cdot (CBR)^{0.711}$	[41]
Georgia Department of Transportation	Granular Materials (Stabilized Limestone)	$E = 31.16 \cdot (CBR)^{0.49}$	[42]
Powell et al (1984)	Soil and granular material	$E = 17.6 \cdot (CBR)^{0.64}$	[43]
Pappula (2008)	Subgrade and Unbound granular material.	$E = 9.79 \cdot CBR$	[44]
Laboratoire Central des Ponts et Chaussées (LCPC) (1995)	Base, Subbase Materials	$E = 5 \cdot CBR$	[40]

and sub-base pavement layers. The main aim is to determine the minimum thickness of these layers containing one of the designed mixtures. The structural pavement is designed based on the French sizing method [39]. This requires knowledge of the elastic modulus of the materials used. In this study, the elastic modulus E of the mixes was estimated based on an empirical relation between E and CBR. Table 9 presents a summary of the existing empirical equations in the literature. Furthermore, the estimation of the elastic modulus was made by using the empirical equation provided by the LCPC French laboratory [40]. The estimated values of E are listed in Table 10, and a fitting curve of these results is shown in Figure 12.

Table 10. Estimation of the elastic module of mixtures

Mixtures	M1	M2	M3	M4	M5
E [MPa]	290	385	465	550	780

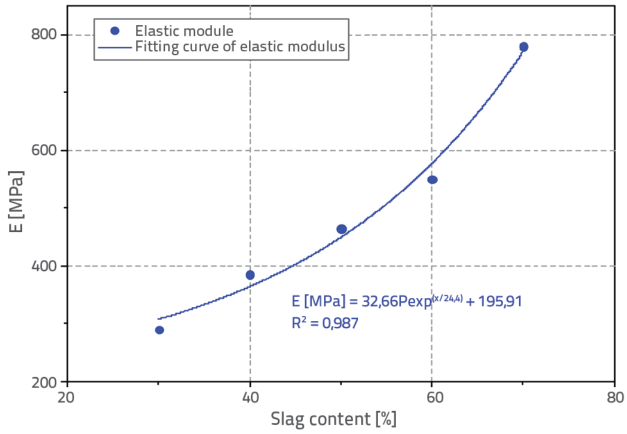

Figure 12. Fitting of modulus elastic of all mixture

The ALIZE-LCPC programme was used to perform pavement design. ALIZE-LCPC is pavement structure calculator software produced by the LCPC [39]. This software is used to generate the value of strain (or stress) at the bottom of a pavement layer under a specific traffic load based on the theoretical model of Burmister [45]. Furthermore, most of the pavement structures used in Morocco are composed of asphalt concrete (AC) in the wearing course and untreated granular materials (GNT) in the base and sub-base courses. The obtained values from the ALIZE-LCPC programme, for this type of structure are compared with admissible ones to verify the performance of the pavement structures that contain the designed mixtures. Pavement sizing is based on the determination of traffic that expresses the number of vehicle passages in a determined period for a roadway. The equivalent cumulative traffic (NE) corresponds to the cumulative number of equivalent axles of 13 tonnes over the considered life. It was calculated using the following equation (Eq. 1):

$$NE = N_{PL} \times CAM \tag{1}$$

Where, N_{PL} is the cumulative number of heavyweights, given by Eq. (2), and CAM is the average aggressiveness coefficient.

$$N_{PL} = 365 \times TMJA \times C \tag{2}$$

Where, TJMA is the average annual daily traffic and C is the cumulative traffic factor for the design time given by Eq. (3).

$$C = ((1 + \tau)^n - 1)/\tau \tag{3}$$

Where, τ is the geometric growth rate of heavy vehicle traffic in percentage, and n is the cumulative period in years.

According to Section 3.3, the M4 and M5 mixtures can only use materials from structures containing GNB-C-D in the base layer. Furthermore, according to the Moroccan guide, these structures are applied for the following traffic classes: TPL1 (0 < TMJA≤5), TPL2 (5 < TMJA≤50), TPL3 (50 < TMJA≤125). In this study, we used the upper limit of the TMJA to find the cumulative traffic value of heavy vehicles (NPL) of each class for a long lifetime (20 years), and for a growth rate of 4 %, i.e., TPL1 corresponds to NPL1=5.037 104 HGVs, and TPL2 corresponds to NPL2=5.037 105 HGVs, TPL3 corresponds to NPL3=1.26 106 HGVs. Values TPL1, TPL2 and TPL3 are equivalent to TC1, TC2 and TC3 of the French Guide of 1998, respectively [46]. The values obtained from the ALIZE-LCPC program for the types of structures subjected to road traffic loading, are compared with the

Table 11. Parameters used to determine the admissible deflection of asphalt concrete

Parameters	ε_6 **(10°C. 25 Hz)**	**E (10°C)** [MPa]	**E (20°C)** [MPa]	**–1/b**	**Sh** [m]	**SN**	**KC**	**Kr**	**KS**	**CAM**
Bituminous materials	$100 \cdot 10^{-6}$	7200	3600	5	0.01	0.25	1.1	0.81	1/1.2	0.5

Table 12. Admissible deformation according the traffic class

Traffic class	**TPL1**	**TPL2**	**TPL3**
Risk [%]	30	18	18
Admissible tangential deformation ($\varepsilon_{t.adm}$**)** [μdef]	307.0	184.5	153.9
Admissible vertical deformation ($\varepsilon_{t.adm}$**)** [μdef]	1446.2	650.5	530.8

Table 13. Calculated thicknesses and deformations for each subgrade bearing capacity under TPL3

Material	**Pf1**			**Pf2**			**Pf3**			**Pf4**		
	Thickness [cm]	ε_t [μdef]	ε_z [μdef]	**Thickness** [cm]	ε_t [μdef]	ε_z [μdef]	**Thickness** [cm]	ε_t [μdef]	ε_z [μdef])	**Thickness** [cm]	ε_t [μdef]	ε_z [μdef]
AC	7	100.7	95.9	7	108.3	91.2	7	123.1	87.7	7	129.2	74.9
M5 as GNT	20	148.6	503.6	20	160.8	510.9	15	189.8	520.5	20	240.5	527.8
M3 as GNT	36	201.7	286.6	24	217.6	288.1	16	233.9	371.7	0	0	0
Pfi	--	201.7	528.2	--	217.6	526.2	--	233.9	521.9	--	240.5	527.7

admissible values to verify the performance of the pavement structure containing the formulated mixtures. The permissible horizontal deformation ($\varepsilon_{T,adm}$) in tension must respect the following expression for bituminous materials Eq. (4):

$$\varepsilon_t < \varepsilon_{t,adm} = \varepsilon_6 \cdot [E(10\ °C)/(E(25\ °C)]^{1/2} \cdot (NE/10^6)^b \cdot K_c \cdot K_r \cdot K_s \qquad (4)$$

where:

ε_t - the horizontal deformation of bituminous materials
ε_6 - deformation because of a million loads
E - elastic modulus
b - slope of the fatigue line
Sh - standard deviation on the layer thickness
K_r - risk coefficient
K_c - calibration coefficient
K_s - coefficient considering the heterogeneity of the bearing capacity of the support.

able 11 shows the parameters used for determining the tangential deformation of asphalt concrete material. For granular materials, the admissible vertical deformation ($\varepsilon_{z,adm}$) in compression is calculated by the following expression Eq. (5):

$$\varepsilon_z < \varepsilon_{z,adm} = A \times (NE)^{-0,222} \qquad (5)$$

Where, A is a factor equal to 0.016 for NE < 2.510^5 and 0.012. The CAM is equal to one for granular materials and 0.5 for bituminous materials for the traffic classes studied. Table 12 shows the allowable distortion values according to the traffic class: An analysis study was performed using the ALIZE software for pavements containing a combination of the mixes M3-4-5 (potential mixes to be used in pavement layers). Additionally, M4 and M5 mixes will be used for the base course and M3 and M4 mixes for the sub-base course. Furthermore, the different existing subgrade bearing capacities were considered. Four types of soil are mentioned in the Moroccan guide, which are: Pf1, Pf2, Pf3, and Pf4 with elastic moduli of 20, 50, 120, and 200 MPa, respectively. The interfaces between the layers are assumed to be bonded.

Table 13 presents a case study of a pavement structure containing M3 and M5 mixes, respectively, in sub-base and base layers subjected to TPL3 traffic. Calculations were conducted for each subgrade bearing capacity (Pf1, Pf2, Pf3 i Pf4). Furthermore, admissible deformations, mentioned in Table 12, are respected. The minimum thicknesses are listed in Table 13. The thicknesses decreased as the soil bearing capacity increased. In addition, the Moroccan guide recommends layer thicknesses ranging from 4 to 7 cm for the surface layer, 10 to 20 cm for the base layer, and 15 to 35 cm for the sub-base layer, depending on the traffic class and soil bearing capacity. The thicknesses (of designed mixtures) are highly similar to those (of conventional materials) specified in the Moroccan guide.

Table 14 shows the minimum thicknesses of the base and sub-base layers of each possible structure of the different combinations between M3, M4 and M5 designed mixtures. Structures 1 and 2 (Structure 2 was developed in Table 13) provide reasonable thicknesses that are close to those recommended by the Moroccan guide. In addition, structure 3 is verified only for TPL1 and is not recommended for TPL2 and TPL3 thicknesses.

Table 14. Thicknesses of road layers containing M3, M4 i M5 that verify the allowable deformations

Structure	**Material**	**Thickness** [cm]											
		TPL1				**TPL2**				**TPL3**			
			Pf2	**Pf3**	**Pf4**	**Pf1**	**Pf2**	**Pf3**	**Pf4**	**Pf1**	**Pf2**	**Pf3**	**Pf4**
Structure 1	AC	4	4	4	4	5	5	5	5	7	7	7	7
	GNT (M5)	12	10	12	10	20	18	10	14	20	20	15	20
	GNT (M4)	16	10	0	0	29	21	10	0	34	22	15	0
Structure 2	AC	4	4	4	4	5	5	5	5	7	7	7	7
	GNT (M5)	14	10	12	10	20	20	15	10	20	20	15	20
	GNT (M3)	15	11	0	0	32	20	15	10	36	24	16	0
Structure 3	AC	4	4	4	4	--	--	--	--	--	--	--	--
	GNT (M4)	15	10	14	11	--	--	--	--	--	--	--	--
	GNT M3)	16	13	0	0	--	--	--	--	--	--	--	--

4. Conclusion

An experimental study was conducted to investigate the potential use of steel slag waste as an alternative material for pavement sub-base and base courses. A thorough characterization was conducted on the raw material, steel slag, to determine its chemical, mineralogical, geotechnical, and mechanical properties. Samples of mixtures composed of slag and waste rock were submitted to laboratory tests to determine their physical and geotechnical characteristics. The results were finally confirmed by the requirements of national standards. In addition, a design study was conducted to determine the thickness of the pavement layers containing the waste mixtures. The following conclusions were reached:

- The mineralogical structure of the steel slag is complicated and rich, containing the following mineral phases: Fe2.95Si0.05O4, $CaSiO_3$, $CaCO_3$, MgO, Ca_2FeAlO_5: $Ca_2Al(AlSi)$O7, $Ca_3Mg(SiO_4)_2$, Ca_2SiO_4. And the chemical analysis of the slag shows that it contains a high level of iron oxide, Fe2O3, at 31.23 % and lime of 29.31%, resulting in a higher density compared to natural aggregates.
- Steel slag has a higher density and excellent fragmentation resistance compared to natural aggregates. The grain size of steel slag has an impact on its ability to compact and does not contain any filler.
- The steal slag waste cannot be used directly as substitute materials for base and sub-base layers because it contains a low proportion of fillers. It is recommended to mix the steel slag waste with another material that contains the required fraction of fillers. In this study, sterile waste was used to produce a full substation of conventional materials from waste.
- The CBR and IPI of the mixtures increase with the slag content because of the grain morphology and fragmentation resistance of the slag, allowing us to conclude that the addition of steel slag to the granular mixtures increases their performances, as shown in Figure 11c.
- Geotechnical and mechanical properties of mixtures M4 (60 % of SS) and M5 (70 % of SS) verified the required properties of conventional materials used in the base layer of pavements. Therefore, it is recommended to use at least 60 % of steal slag waste to produce such alternative material.
- For the sub-base layer, the mixtures M2 (30 % SS) to M5 are all recommended.
- Pavement design thicknesses of mixtures used in pavement layers are reasonable and comparable to those of conventional materials.

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