CETRA2020* 20-21 May 2021, Zagreb, Croatia
6th International Conferenceon Road and Rail Infrastructure

RECYCLING CONSTRUCTION AND DEMOLITION WASTES WITHIN HYDRAULICALLY BOUND MIXTURES FOR ROAD PAVEMENTS

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Abstract

The recycling of Construction and Demolition Waste (CDW) is an actual challenge regarding the construction industry because of the increasing volumes worldwide produced and the related environmental impacts. In this regard, a suitable application can be developed in the road construction field, in particular for the production of hydraulically bound mixtures for road subbase and foundation layers. In this sense, the reuse of CDW can strongly enhance the environmental sustainability of road construction thanks to the achievable savings of natural resources such as the mineral aggregates obtained from quarry operations. Indeed, the utilization of a CDW as aggregate must ensure the production of mixtures with adequate mechanical and environmental characteristics. Therefore, the herein paper presents the results of an experimental characterization aimed at assessing the suitability of CDW for the production of hydraulically bound mixtures for road pavements. In particular, the main mechanical properties of some mixtures including different percentages and gradations of CDW were analysed and compared with the main technical prescriptions and classification criteria indicated by the reference European standards. Basic properties and production processes of the CDW materials were also studied to determine their effects on the optimum binder and water contents of the mixtures. The research clearly demonstrated that the use of a preliminary-washed CDW coarse aggregate was able to enhance the overall structural properties and the water resistance of mixtures.

Keywords: construction and demolition waste, cement treated mix, road materials, European standard classification, laboratory characterization

1 Introduction and research objective

The reuse of Construction and Demolition Waste (CDW) is an actual challenge concerning the construction filed and the building industry because of the increasing volumes produced worldwide. Concerning this point, Europe generated more than 800 million tonnes of CDW in 2016, overtaking the annual production of the United States in the same year (700 million tonnes). Today, the largest and populated countries are able to create more than 10 billion tonnes of CDW by year [1]. Statistical projections estimated also that the production trend is increasing with a non-negligible rate [2]. Generally, CDW consists in a debris that can comprise steel, wood, drywall and plaster, brick and clay tile, asphalt shingles, concrete and asphalt concrete as by-products resulting from construction, renovation and demolition activities [3]. Several CDW-related environmental impacts (land and water pollution, space occupation, greenhouse gas emissions, energy consumptions, etc.) have been widely documented in literature [4], [5]. Actually, CDW is recycled as secondary aggregate in many construction fields (buildings, roads and bridges and other sectors). A suitable application can be developed in road constructions, in particular within hydraulically bound mixtures for road subbase and foundation layers [6], [7]. Such solution can strongly enhance the environmental sustainability of roads, thanks to the achievable savings of natural resources such as the mineral aggregates obtained from quarry operations that are requested for the above-mentioned layers. However, given the extreme heterogeneity of CDW in terms of nature, origin, composition and gradation [8], [9], its recycling in pavements must be adequately designed and executed considering the characteristics requested by the final mixtures for road layers (mechanical performance, environmental properties, etc.). Given this introduction, the present study aimed at evaluating the possible use of different CDW aggregate fractions to produce suitable cement bound mixes for road subbases and foundations. To accomplish this goal, a laboratory plan was arranged to test different mixtures including various CDW stockpiles and evaluate their structural performance in comparison to the main technical prescriptions and classification criteria indicated by European standards. EN 14227-1 and EN 14227-15 were assumed as references for the mechanical properties and the water susceptibility of the mixes, respectively. Fine and coarse fractions were used to estimate the role of aggregate size and the influence of granulometric distribution. Moreover, the use of stockpiles subjected to different preliminary treatments allowed establishing the best practices to reuse the CDW coming from common construction sites in order to maximize the materials performance for road pavements deep layers applications.

2 Materials, sample preparation and test methods

Four CDW aggregate stockpiles were selected for the experimentation. In particular, the gradation of two stockpiles was between 0 and 6.3 mm (they were named "fine aggregates"), whereas other two had gradations between 0 and 31.5 mm (they were identified as "coarse aggregates"). All CDW derived from an Italian construction site. The two fine aggregates had the same origin and were initially subject to a preliminary treatment process with the objective to remove metallic, glass and organic residues. Then, the first one was utilized as it was (hereafter coded F); the second one (hereafter named F_w) was additionally washed with water in order to dispose further impurities (mainly, cohesive or granular particles with size < 0.100 mm were eliminated). In the case of coarse stockpiles, the same procedure was followed: after the initial selection, a non-washed coarse aggregates (hereafter coded C) and a washed one owing the same origin (hereafter named C_w) were obtained. Even no additional information about stockpiles nature was available (e.g., fine part plasticity index), clear effects due to water-washing were noticed in their final gradations. In this perspective, Figure 1 illustrates some images of such aggregates, whereas Figure 2 presents their granulometric distributions. Combining the aggregate portions, four cement bound mixtures were produced: their composition was chosen in order to produce different granulometric combinations complying with specifications proposed by EN 14227-1: in particular, the grading envelope for cement bound granular mixtures of type 1 (0/31.5) and category G1 was considered. The codes of the produced mixes and their proportions are given in Table 1, whereas Figure 3 presents the resulting mixture lithic matrixes (plots are split for the sake of clarity). A Portland cement type II/B-LL 32.5 R (EN 197-1) was utilized as binder. Its dosage, together with the water content, was optimized according the mix design procedure described below.

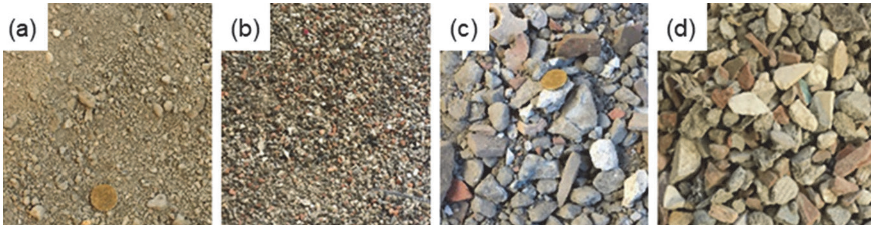

Figure 1 Images of the selected CDW aggregates: a) F, b) F_w, c) C, d) C_w

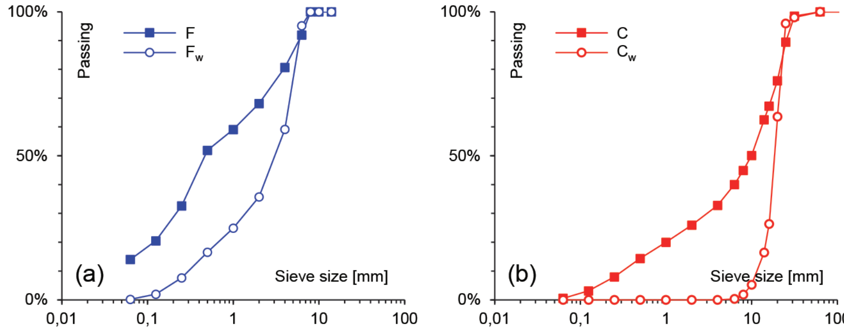

Figure 2 Gradations of selected stockpiles: a) fine aggregates F and F_w, b) coarse aggregates C and C_w

Table 1 Mixture compositions and proportions

Mix code	Constituents			
	F	F_w	C	C_w
FC	30%	-	70%	-
FCC_w	20%	-	70%	10 %
FF_wC_w	20%	30%	-	50 %
FF_wCC_w	15%	20%	30%	35 %

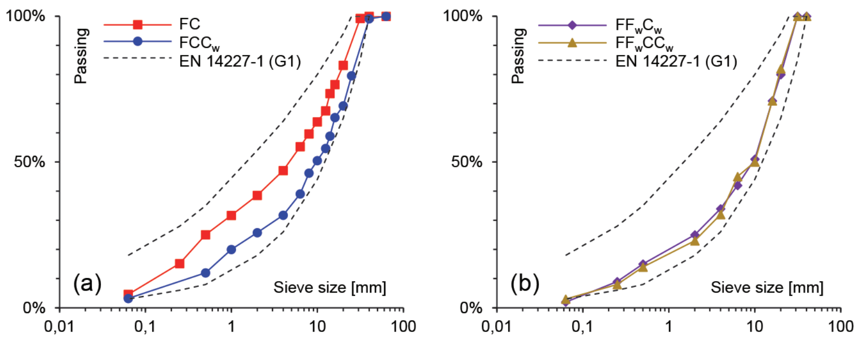

Figure 3 Final gradations of mixtures:a) FC, FCC_w, b) FFwCw, FF_wCC_w

Cylindrical 150 mm-diameter specimens were produced in the laboratory for each mixture through the Proctor modified procedure (reference standard EN 13286-50). In the early experimental stage, samples were replicated using different cement (c) and water (w) contents to optimize the mixtures. Three replicates for each cement-water dosages were compacted. The optimization was then based on the mechanical properties exhibited by specimens (compressive and tensile strengths at 14 days). Once obtained the optimum c/w contents, further samples were reproduced for the selected mechanical characterization. First, indirect tensile strength tests at 7 days were performed determining R_{ti} parameters and the direct tensile strengths were estimated using the standardized relationship $R_t=0.8 \cdot R_{ti}$ (reference standard EN 13286-42). Then, compression tests were executed to determine strength R_c (reference standard EN 13286-41). Such R_c was coupled with compressive stiffness tests and was used to calculate the modulus of elasticity E_c of the mixtures, then to estimate the modulus at 7 days using the standard relation $E=E_c$ (reference standard EN 13286-43). Overall results were utilized to classify the cement bound mixes according to the specifications given by EN 14227-1. The final step of the study concerned the study of the water influence in the mechanical properties of the materials. To this purpose, laboratory specimens (produced at c/w optimum content) were classified using EN 14227-15 standard: after four days of water immersion, they were analysed in terms of compressive strength ratio (R_i/R between cases with and without immersion, according to EN 13286-41), linear swelling LS (reference standard EN 13286-47) and CBR (reference standard EN 13286-47). EN 14227-15 applies to soils rather than to aggregates, but it was used in order to have further criteria suitable for characterizing and classifying the materials.

3 Results and discussion

3.1 Mix Design

The mix design of each mix consisted in determining the optimum Portland cement dosage and the optimum water content: the results are presented in Table 2 whereas the following Figure 4 illustrates an example of the procedure applied to FF_wCC_w mixture (compressive and tensile strength optimizations presented in Figures 4a and 4b respectively are considered to determine the final average adopted water content w). Main findings indicated that the maximum water content was requested in the case of FC mix (non-washed fine and coarse aggregates). At an equal c dosage (3.5 %), FCC_w (mix with washed coarse aggregate) had a lower optimum w (7.3 %). Supposing a greater presence of fine plastic particles (not eliminated by the washing) for FC, this seemed to be slightly in contrast with existing literature stating that higher clay-like particles can reduce the water requested for the optimum mix design [10]. However, such a finding should be read considering that the possible presence of porous lateritious constituents in the coarse CDW can alter the natural w equilibrium, thus also the cement hydration [11]. When washed fines F_w were included in the lithic skeleton, no evident variations in the optimum contents were detected, despite the overall different percentages of fine and coarse fractions (3.0 % of c for both mixtures, 8.2 % and 8.3 % of w for FF_wC_w and FF_wCC_w, respectively). In general, the preliminary washing of the stockpiles led to a reduction of the requested water or cement; thus, it could be read as a positive factor in the overall economy of mixtures. Otherwise, based on the proposed results, it was not possible to better identify the role of the washed fine or coarse fractions. Furthermore, no additional indications could be drawn at this stage of the study: probably, future experimentations should be addressed to compare non-washed vs. washed aggregate establishing the global proportion of mixtures, as well as to strictly determine the influence of possible lateritious parts in the stockpiles.

Table 2 Results of the mix design

Mix code	Cement c (by agg. weight)	Water w (by agg.+c weight)
FC	3.5 %	10.8 %
FCC_w	3.5 %	7.3 %
FF_wC_w	3.0 %	8.2 %
FF_wCC_w	3.0 %	8.3 %

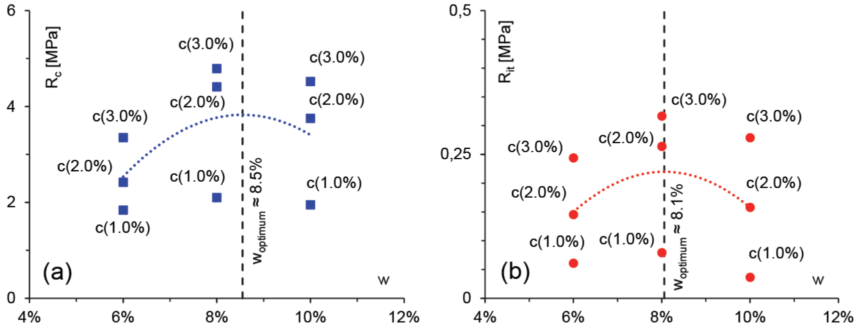

Figure 4 Mix design of FF_wCC_w mixture: R_c (a) and R_{it} (b) vs. c and w

3.2 Mechanical properties and mix classification according to EN 14227-1

The results of the mechanical characterization concerning the optimized samples (optimum c and w) are here summarized. Table 3 reports compressive strength values R_c, intended as the average of three test replicates: strength categories according to EN 14227-1 are also reported. Further information on materials can be collected also from Figure 5, in which mixes are described in terms of elastic modulus and tensile strength and are classified according to the EN 14227-1 (category based on E and R_t). As far as the compressive strength concerns, the non-washed mixture FC reasonably presented the lower resistance. Progressively including the washed portions, R_c values increased: in particular, it seemed that the addition of C_w enhanced the resistance of the corresponding mixture containing C (see the comparison between FC and FCC_w, or FF_wC_w vs. FF_wCC_w). As a result, the resistance classes (EN 14227-1) related to C_w-containing mixes were always greater than the others (FCC_w and FF_wCC_w owned $C_{2.3/3}$ labels, FC and FF_wC_w had $C_{1.5/2}$). On the contrary, the only addition of F_w (e.g., see FC vs. FF_wC_w) did not allow to improve the compressive strength class (even if R_c slightly increased passing from 2.79 to 2.83). With respect to E and R_t values, similar indications could be collected. Otherwise, analysing Figure 5, it was found that E-R_t class did not vary (T1 label for all the mixtures), regardless the increments of the values. Overall, it was finally stated that the use of washed stockpiles rather than non-washed ones was able to improve the characteristics of the mixes, but the inclusion of washed coarse aggregates (C_w) had the greatest impact (it led to the increments of compressive resistance class).

Table 3 Compressive strength results and related EN 14227-1 classes

Mix code	FC	FCC_w	FF_wC_w	FF_wCC_w
R_c [MPa]	2.79	3.45	2.83	3.02
R_c class [EN 14227-1]	$C_{1.5/2}$	$C_{2.3/3}$	$C_{1.5/2}$	$C_{2.3/3}$

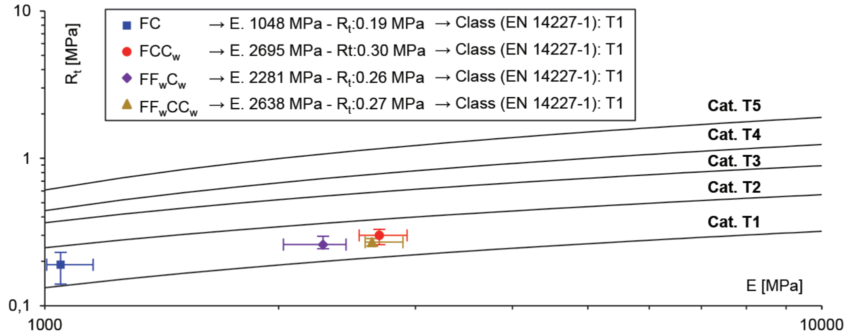

Figure 5 Figure 5. E and Rt experimental results and classification (EN 14227-1)

3.3 Water sensitivity and mix classification according to EN 14227-15

Based on the results presented in Table 4, the compressive strength ratio between dry and water-conditioned samples indicated good water resistance for all cases (R_i/R always greater than 0.8). The use of F_w (washed fine) did not seem to influence the results, whereas C_w (washed coarse) produced a significant increase of the observed parameter, regardless the coupling with washed or non-washed fines. Analysing the linear swelling behaviours, despite the variability of the values, LS parameter could be considered negligible in all mixes (always included in EN14227-15 LS_1 class). Thus, the selected construction and demolition waste can be adopted for the construction of road subbases and foundations without particular expansion issues in presence of water (no specific cares are needed for the presence of humidity in the construction site or for possible moist environments) [12]. Based on CBR results collected after 4 days of soaking in water, the role of C_w aggregate was again detected (with respect to the corresponding mixes, the C_w-containing materials had always the greater CBR). Overall, considering the water susceptibility of the produced mixes, laboratory findings indicated the possibility of producing water-resistant cement bound materials including in the gradations the washed coarse aggregate fraction.

Table 4 Water influence: classification according to EN 14227-15

Mix code	FC	FCC_w	FF_wC_w	FF_wCC_w
R_i/R [-]	0.8	1.0	0.8	1.0
R_i/R class [EN 14227-15]	$I_{0.8}$	$I_{1.0}$	$I_{0.8}$	$I_{1.0}$
LS [%]	0.055	0.060	0.030	0.025
LS class [EN 14227-15]	LS_1	LS_1	LS_1	LS_1
CBR	255	525	250	310
CBR class [EN 14227-15]	CBR_{255}	CBR_{525}	CBR_{250}	CBR_{310}

4 Conclusions and further studies

The study proposed an experimental characterization aimed at evaluating the possibility of using only CDW aggregate for the construction of road subbases and foundations. Some concerns about the preliminary treatment of CDW were also analysed. Based on the obtained results, the main findings indicated a good suitability of the selected coarse aggregate when subjected to a preliminary washing. In this case, the conventional removal of metallic, glass and organic residues was integrated with a cleaning treatment performed with water, which partially alters the original CDW grading and was reasonably able to eliminate further impurities (principally, fine clay-like particles with cohesive characteristics). Therefore, including such a stockpiles in cement bound mixes having a gradation complying with envelop given by European standards, a reduction of the optimum water content (beneficial for the mixture economy), an improvement of the compressive resistance category and some clear increases in the values of tensile strength and elastic modulus can be ensured, whatever the treatment process applied to the CDW fine. In turn, this addition provided water-resistant mixtures that did not need particular care when adopted in humid and moist construction environments. Further improvements of the research could include the modification of the mix-design in order to keep constant some constituent proportions and definitely account the contribution of the single fractions. Some ongoing studies are also trying to characterize the CDW source materials with the target to understand how the typical heterogeneity of such a waste will affect the final properties of cement bound mixes for road pavements.

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