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SHORT-TERM AND LONG-TERM EFFECTS OF CEMENT KILN DUST STABILIZATION OF CONSTRUCTION AND DEMOLITION WASTE

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ABSTRACT

High volumes of construction and demolition waste (CDW) are continuously produced worldwide. The European Commission aims to increase the recycling of non-hazardous CDW to a minimum of 70% in weight terms by 2020. Hence, there is increasing pressure on researchers to focus on the valorization of these alternative materials for use in the world of construction alongside traditional materials.

CDW contains materials from excavation and/or demolition and are typically heterogeneous in terms of composition, grain size, and toughness; furthermore, some particles are more sensitive to degradation processes than others. One solution for an increase in durability while maintaining sufficient strength levels is chemical stabilization with cementitious binders.

The paper illustrates the results of a laboratory investigation into the properties of CDW when subject to stabilization with cement kiln dust (CKD). Mixtures of CDW stabilized with ordinary Portland cement (OPC) were prepared for comparison purposes. The results obtained with CKD are encouraging since it increases the strength and stiffness of CDW, thus leading to a material completely made up of recycled wastes and by-products usable in the formation of pavement subbases and subgrades. As regards the curing time, all mixtures saw a significant increase in their mechanical parameters when passing from 7-28 days to 365 days of curing.

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INTRODUCTION

Construction and demolition waste (CDW) is derived from the recycling and treatment of waste products from construction, renovation, or demolition activities, thus its composition varies considerably in terms of gradation and quality of constituent materials (Molenaar and van Niekerk 2002). The most common recycled materials in CDW are concrete, asphalt, bricks, gypsum, glass, soil, and sometimes rock demolition and quarry waste. Occasionally, CDW also includes leavings of wood, plastic, and metals.

CDW accounts for approximately 30% of the total waste produced in the European Union (European Commission 2011). This percentage depends on the intensity of renovation of civil constructions and on general economic trends. From 2005 to 2015, an average annual increment of 0.7% in CDW was recorded (European Commission 2011). The objective of the 2008/98/EC Directive is to increase the use of recycled non-hazardous waste resources in place of natural materials to a minimum of 70% (by weight) by 2020 (European Parliament 2008). As a result, most of the European companies that mine and process aggregates now collect and grind wastes from construction and demolition works to produce a variety of commercially viable CDW aggregates.

Although CDW has been used in road constructions for two decades, its use is currently intensifying thanks to the support of research, which has demonstrated that aggregates from CDW (in the form of clean aggregate – i.e. from a single origin such as concrete, brick or asphalt – or aggregate in which several elements are mixed together) are an alternative to natural aggregates (Sherwood 2001). Its strategic use would lead to a reduction in the employment of non-renewable raw materials in applications that do not require high performances.

The composition and gradation of CDW aggregates affect its optimum moisture content (OMC) and maximum dry density ($\rho_{d,max}$). Poon and Chan (2006) evaluated the $\rho_{d,max}$ and OMC of a mixture of recycled concrete aggregate (RCA) and crushed brick (CB), concluding that it exhibits higher OMC and lower $\rho_{d,max}$ levels than those of natural aggregate. Moreover, as the CB content increased in the mixture, the $\rho_{d,max}$ tended to decrease and the OMC to increase due to the higher water adsorption attitude of CB. Arulrajah et al. (2012) studied the five most common elements of CDW namely: RCA, CB, waste rock (WR), reclaimed asphalt pavement (RAP) and fine recycled glass (FRG). Results from modified Proctor tests showed values of OMC from 8.0% for RAP to 11.2% for CB, and indicated that WR had the highest $\rho_{d,max}$ while FRG had the lowest one.

Bennert et al. (2000), Molenaar and Niekerk (2002), Gabr and Cameron (2011), and Cerni and Colagrande (2012) used the resilient modulus test to estimate the stiffness of CDW. Results demonstrated that CDW performs similarly to and sometimes better than virgin unbound granular materials. For example, Bennert et al. (2000) recorded higher resilient moduli for RCA and RAP than for dense graded aggregate base course materials (DGABC). For a bulk stress of 145 kPa, they found a resilient modulus of 116 MPa for DGABC, 263 MPa for RAP and 262 MPa for RCA, while for a bulk stress of 345 kPa, the resilient modulus was 180 MPa for DGABC, 361 MPa for RAP and 376 MPa for RCA.

Da Conceição Leite et al. (2011) pointed out that compaction can result in the crushing and breakdown of CDW particles; Vegas et al. (2010) observed that the presence of concrete and ceramic particles can lead to pozzolanic reactions, which contribute to an increase in the bearing capacity of the layer in which they are present.

Conversely, Bennert et al. (2000) observed that RAP waste exhibits a higher rate of permanent deformations than natural DGABC and RCA. After 10^5 loading cycles at a deviatoric stress equal to 310 kPa, the magnitude of the permanent strain of RAP was 0.056 mm/mm, while values of 0.007 and 0.004 mm/mm were observed for DGABC and RCA respectively. One solution for the prevention of excessive permanent deformation in the long term, could be the chemical stabilization of CDW.

As previously reported, CDW exhibits mechanical properties with wide-ranging values because of its heterogeneous and extremely variable composition. In some applications, strength and stiffness requirements necessitate stabilization with binders or blending with high quality aggregates to enable its usage in pavement layers (Arulrajah et al. 2012). The addition of binders to unbound granular materials allows us to achieve higher strength, lower permeability and lower compressibility (Papagiannakis and Masad 2008).

A stabilization of CDW with ordinary Portland cement (OPC) has been repeatedly proposed to enhance the performance of road base and subgrade layers (Houben et al. 2010, Taha et al. 2002, Puppala et al. 2011).

Taha et al. (2002) evaluated the effects of stabilization with OPC on RAP in terms of OMC, $\rho_{d,max}$, and unconfined compressive strength (UCS). Houben et al. (2010) analyzed the performance of a cement treated granulate mix with crushed masonry and RCA, concluding that UCS and indirect tensile strength increased linearly with increases in cement content, curing time and degree of compaction. Other stabilizer alternatives have been proposed and experimented with, like fly ash, cement kiln dust, and silica fume (Little and Nair 2009, Sabat and Pati 2014), since ordinary cementitious products are usually more expensive than by-products.

The use of cement kiln dust (CKD) has been proposed since the nineties (Miller et al. 1980, Baghdadi and Rahman 1990, Baghdadi et al. 1995, Miller and Zaman 2000, Peethamparan et al. 2008, Solanki et al. 2010). CKD is a by-product of cement manufacturing and passes out of the top of the preheater with the exhaust gases or, more typically, out of the back of a long wet or long dry kiln. It is composed of micron-sized particles collected from electrostatic precipitators, and contains a lower level of oxides than an OPC (Miller and Azad 2000). The chemical composition depends on the clinker raw meal and fuel used in the process, and the burning process conditions (i.e., temperature, composition of gases, etc.). Hence, its composition and properties can vary, even at the same plant.

Ebrahimi et al. (2011) tried to improve the stiffness of road surface gravel and RAP by adding a quantity of CKD, which did not exceed 15% in weight terms of the aggregate. The seismic modulus of specimens increased to values between 5 and 30 times greater than those for untreated materials, but this improvement was inferior to that induced by OPC stabilization. Halles and Thenoux (2009) observed better mechanical properties and long-term performance when using CKD in place of fly ash. Miller and Azad (2000) investigated the effects of CKD addition to three different soils with high, medium, and low plasticity. The increase in CKD content in the mixtures resulted in a decrease in the $\rho_{d,max}$ and plasticity index and an increase in OMC and UCS. Until now, the stabilization of CDW with CKD has not been documented in literature.

This paper evaluates the physical-mechanical properties of CDW, both untreated and stabilized with traditional (OPC) or alternative (CKD) binders. In this experimental investigation, two different classes of CDW with grain sizes up to 25 mm (0-25 mm) and 8 mm (0-8 mm) respectively were collected from a full-scale plant. These two classes of CDW were also treated with different percentages of OPC and CKD to evaluate the potential of CKD stabilization, while also considering the time related-effects on the mechanical properties of different combinations of mixtures. Tests were carried out on mixtures cured from 0 to 365 days. Additionally, the temperature evolution over the mixing phase was monitored to evaluate possible moisture loss resulting from the significant exothermic reaction of mixtures containing a high binder content like those selected for the CKD.

MATERIALS AND METHODS

Base materials

CDW aggregates employed in this investigation were sampled in a crushing plant located in the metropolitan area of Turin (Italy), and supplied in two size fractions, 0-8 and 0-25 mm (Figure 1). To limit the use of natural resources, current technical regulations adopted in the North-West of Italy permit the use of recycled aggregates in road constructions. In most of the North of Italy, a significant amount of granular materials employed in the formation of embankments is essentially recycled CDW. Figure 1 shows the Italian (CIRS 2001) and American (AASHTO M147 Type D) specification limits for stabilized granular materials; the grading curve of CDW 0-25 mm falls entirely within both limits, while the finer CDW 0-8 mm follows the upper limit of the AASHTO specification (AASHTO 2012a).

A preliminary characterization of the CDW was performed to assess its physical properties. As per the current European Standards, particle density (EN 1097-6), shape (EN 933-4), and flakiness index (EN 933-3) were evaluated. Table 1 indicates that recycled aggregates are characterized by small quantities of flat and elongated particles. These values, when compared to those obtained for a traditional aggregate, are relatively high due to the presence of pottery shards and bricks.

The compaction parameters of the two CDW materials were evaluated by means of the Proctor method according to EN 13286-2 (European Standards 2010), and results are summarized in Figure 2. The differences in OMC values depend on grain size distribution, since finer grains (0-8 mm) have a higher specific surface than coarser ones (0-25 mm) and adsorb more water (w). The differences in maximum dry density ($\rho_{d,max}$) values are also attributable to size distribution, since the 0-25 mm is well graded and allows finer particles to fill the voids left by coarser grains.

Two different binders were used to stabilize the recycled aggregates, an OPC classified as CEM II/B-P 32.5 R according to EN 197/1 (European Standards 2011), and a CKD. The chemical composition, the size distribution, and the strength evolution over time of each binder is listed in Table 2.

Loss on ignition (LOI) in Table 2 represents the percentage of mass lost at temperatures of 950°C. The main contribution to mass loss at this temperature comes from CO_2 loss from $CaCO_3$, which is higher in CKD than in OPC.

Table 2 summarizes the characteristics of the binders in terms of volumetric stability, setting times, flow, density, specific surface, and compressive strength in line with European Standards. The selected binders have very different setting times ranging from a few hours in the case of cement, to several hours in the case of CKD. The flow test is performed on samples of standard mortar with a fixed volume of water equal to $2.25 \cdot 10^{-4}$ m^3.

Due to its greater fineness, particle shape, and chemical composition, CKD requires a higher water content than OPC to reach the same consistency. The specific surface of CKD is particularly high due to the presence of volatile particles. The volumetric stability is measured by means of the Le Chatelier apparatus, which anticipates any possible deficiency due to late expansion of uncombined calcium and/or magnesium oxide. It magnifies any expansion during heating in boiling water.

Finally, Table 2 summarizes strength development from 1 to 28 days of curing. CKD has a low cementing capacity since it takes longer than OPC to reach a very low strength value. In fact, compared to OPC, CKD exhibits a weak binding behavior due to the limited content of oxides; hence, it has to be employed in larger quantities.

Mixtures

Table 3 lists the eight mixtures, two made up of CDW only, and six made up of CDW stabilized with OPC or CKD, together with the total number of replicates per mixture. Stabilized mixtures were prepared by considering the amount of water necessary to reach the OMC, and to develop the hydration processes. The optimal moisture content was derived from data collected in literature.

In the case of OPC stabilization, a 0.5% increase in optimum moisture content (OMC) was assumed for every 2% of binder added. In the case of CKD, the OMC_s of the stabilized mixture was considered as a function of the OMC_a of the corresponding mixture containing only recycled aggregates, and the percentage by weight of CKD (%CKD), by means of the following linear equation:

$$\mathrm{O}MC_{\mathrm{s}} = \mathrm{OMC_a} + \bar{a} \cdot \%\mathrm{CKD} \quad (1)$$

where $\bar{a}$ is a regression coefficient. Eq. 1 was obtained from the data analysis reported in Miller and Azad (2000) and Ebrahimi et al. (2011), in which a mean value of the coefficient $\bar{a}$ was also calculated as 0.1620. Table 3 contains the OMC_s of the investigated mixtures, and the $\rho_{d,max}$ values obtained from a Proctor test. As predicted in Miller and Azad (2000), Ebrahimi et al. (2011), Amadi and Lubem (2014), the addition of CKD always caused an increase in OMC and a reduction in $\rho_{d,max}$ values.

Due to the exothermic nature of hydration reactions, mixing any hydraulic binder with water and aggregates generates heat that might cause a loss of moisture. To better understand this phenomenon, a digital thermometer was inserted into the material after mixing and data recorded for 10 min (Figure 3a).

It should be pointed out that the loss of moisture necessary for the hydration reaction is also due to the absorptivity of the interfacial transition zone (ITZ) between the recycled aggregate and the cement paste. Its origin lies in the packing of the cement grains against the much larger aggregate, which leads to a local increase in porosity and water absorption, and a consequential decrement in the mechanical properties of the final hardened mixture (Scrivener et al. 2004).

The experimental investigation was performed in a laboratory where average conditions of humidity and temperature (around 25°C) were maintained at a constant for the duration of the tests.

The temperature increment was observed to be strongly dependent on the type and dosage of binder used, varying between 1.4°C in the case of CDW25 with 2% of cement and 9.7°C for the same aggregate type with 20% of CKD. Despite these relatively high temperature increments, the moisture loss was less than 0.2% in the case of mixture CDW25+CKD20 (Figure 3b) although it was approximately twice that of the OPC mixture. Lower values of moisture loss were recorded for other mixtures. Although at the laboratory scale the variation in moisture seemed negligible, it is advisable to take this phenomenon into account in situ, where the larger quantity of material and greater surface area exposed to the air can have significant large-scale effects.

Sample preparation and testing program

The $\rho_{d,max}$ was used as a target value for the production of samples at the gyratory shear compactor (GSC). To appreciate the evolution of densification parameters during the compaction process, the authors also used the GSC with unbound and stabilized granular materials to provide indications useful in in-field laying operations (Riviera et al. 2014).

The volumes of dry material and water to be introduced into the mold were calculated to obtain the target $\rho_{d,max}$ (Table 3) for cylindrical samples of 200 mm in height and 100 mm in diameter. Samples were compacted into four layers to facilitate an equal distribution of the compaction energy.

The compaction process was modelled on the following linear equation:

$$C_x = C_1 + k \cdot \log N \qquad (2)$$

where C_x is the degree of compaction reached by the mixture after N gyrations, k and C_1 are regression coefficients representing the workability and self-compaction of the mixture respectively. The degree of compaction is the percentage of a theoretical compaction relative to the zero-voids density condition. The average values k and C_1 for the four layers in which every sample was divided, were estimated and associated with the mixture.

Once prepared, the samples were placed into plastic molds for 7, 28, and 365 days with each sample sealed by wrapping it in plastic film to prevent any water loss. Samples were not stored in humid rooms or chambers, since their internal conditions do not reflect in-field conditions for 365 days of curing.

The mixtures were subjected to dynamic and static loading tests to assess their behavior under different load conditions. The resilient modulus (RM) test according to AASHTO T307 (AASHTO 2012b), and the UCS test following the ASTM D2166 (ASTM 2013) were then conducted at 7, 28, and 365 days. In the case of the RM test, samples cured at 7 days were tested once again at 28 days together with a set of new samples. The procedure aimed to verify whether simulated test stress conditions affected the samples. The RM test was carried out with a triaxial apparatus in which the LVDTs are mounted outside the cell. Before starting the triaxial tests, the samples were demolded and the plastic film was removed and replaced with a latex membrane. In the case of the UCS test, the samples were simply demolded and placed between the platens of the load test apparatus.

The UCS allows the evaluation of the elastic and fracture properties of materials (Mamlouk and Zaniewski 2011). As is evident in Figure 4, the stress-strain curvilinear relationship allows the definition of the initial tangent modulus as the slope of the tangent of the stress-strain curve at the origin, and the toughness as the energy that is required to fracture the material. Figure 4 also includes the secant modulus, which is equal to the slope of a segment drawn from the origin to an arbitrary point on the stress–strain curve (Mamlouk and Zaniewski 2011, ASTM E6-02). Usually, the arbitrary point for concrete is considered to be 45% of the maximum compressive strength (ACI 2008), but in this investigation, the authors preferred to select the maximum in order to estimate an average stiffness value along the stress-strain curve.

UCS is also used to assess the mixture excavatability as is the practice for cementitious controlled low-strength materials (Folliard et al. 2008), in which the removability modulus (RE) is estimated with the following formula:

$$RE = 0.619 \cdot 10^{-6} \cdot D^{1.5} \cdot UCS^{0.5} \quad (3)$$

where D is the density in kg/m^3 and UCS is in kPa. Values of RE close to or lower than 1 indicate that the materials can be easily removed using excavators, while higher values mean that the use of hydraulic hammers is necessary to remove the material. UCS tests were carried out at a deformation rate of 0.5 mm/min.

RESULTS AND DISCUSSION

Workability

Table 4 contains the results of the workability analysis conducted using the compaction parameters (k and C_1) collected during the gyratory compaction, and the average number of gyrations that were required to reach the desired $\rho_{d,max}$ (N@ $\rho_{d,max}$). The data in Table 4 shows that CDW25 exhibited the highest values of k and C_1.

The effect of the variation in workability due to the addition of binder is shown in Figure 5. With CDW25, stabilization at 10% of CKD reduces k and C_1, while the addition of another 10% of the binder improves both parameters. The same trend is observed for stabilization with OPC at 2 and 4%. In the case of CDW8, the addition of CKD reduces workability while with OPC it increases; a reduction in self-compaction is observed in both cases. The N@ $\rho_{d,max}$ is considered proportional to the number of passes that the roller should perform in the field to reach the desired level of compaction: the increase in N@ $\rho_{d,max}$ reported in Table 4 tends to reflect the loss in workability (k).

Resilient properties

Resilient modulus (RM) tests were performed on samples cured for 7, 28, and 365 days. As already mentioned, two samples tested at 7 days were tested again at 28 days, and the average percentage difference between the results at 28 days ($\overline{\Delta RM}$) was evaluated, according to the following formula:

$$\overline{\Delta RM} = \frac{\sum_{i=1}^{i=15} 100 \cdot \frac{RM^*_{28,i} - RM_{28,i}}{RM_{28,i}}}{15} \qquad (4)$$

where RM^*_{28} is the resilient modulus at 28 days of samples which had already been tested at 7 days, RM_{28} is the resilient modulus of samples tested only after 28 days, and i represents the generic testing sequence of the 15 envisaged by the AASHTO T 307 standard, which is obtained by changing the confining pressure and the maximum axial stress on the cylindrical samples in the triaxial apparatus.

Values of eq. 4 varied randomly independently of the mixture type. The highest value of variability was observed for the CDW25+CKD10 mixture, equal to 25%. Mixtures CDW25+CKD20 and CDW8+CKD10 showed the values closest to 0 (-0.5% and –1.2% respectively), while the CDW25+CEM4 was at 4.3%, CDW8+CEM2 at 11.8% and finally CDW25+CEM2 at -12.2%. In conclusion, the variations in RM observed passing from 7 to 28 days are relatively low and do not seem to affect the maturation of the stabilized mixtures. As a result, the RM test investigation was prolonged to 365 days for all the samples; in the meanwhile, the samples were wrapped in a cellophane film and stored in the plastic mold for their conservation. This procedure was adopted to safeguard the moisture content level and the integrity of the samples, thus avoiding any loss of mixing water due to exchange with the environment. Unfortunately, it was not possible to store the CDW25 samples properly for a year; in fact, when these samples were demolded, some small parts of the four samples became separated thus compromising their overall integrity. For this reason, it was decided not to subject them to final tests at 365 days of curing.

Figures 6, 7, and 8 show the RM results as a function of the first stress invariant (θ) averaged over two repetitions for samples cured at 7 days, and over four repetitions for samples tested at 28 and 365 days. They also contain the upper and lower limits of typical RM values for granular materials of subbase and base layers indicated in Huang (2003), and suggested by Monismith and Witczak and reported in Shook et al. (1982).

A comparison between RM values obtained from the two classes of untreated CDW is provided in Figure 6. It indicates that the curing time contributes to the increase in stiffness due to the presence of non-inert particles, which generate a pozzolanic activity in the CDW that contributes to the formation of new bonds between particles (Motta 2005). From a comparison of the two graphs, it can be seen that the gradation has a limited influence on the resilient response of the two materials, with a higher RM value for the CDW25.

Figure 7 shows the effects of binder type and content on RM for the same curing time. As expected, the addition of cementitious binders enhanced the stiffness of both recycled materials. In the case of CDW8 stabilized and tested at 7, 28 and 365 days of curing (Figures 7a, 7c, 7e respectively), the addition of CKD resulted in higher values of the RM when compared to OPC. At 28 days, this difference tends to decrease, with only a slight increase in RM values recorded for

OPC stabilized aggregates (Figure 7c), while at 365 days the difference is practically zero (Figure 7e).

For CDW25 mixtures tested after 7 days of curing, stabilization with OPC rather than CKD results in better performances irrespective of the percentage of CKD added (Figure 7b). However, tests at 28 days demonstrate that the type of binder and its composition seem irrelevant to RM (Figure 7d). While curing time had a negligible effect on samples with CKD, samples with OPC showed lower values of RM at 28 days than at 7 days. It seems that CKD acted independently of curing time, since the differences in RM recorded between 7 and 28 days of curing are negligible. In contrast, samples with OPC showed lower RM values at 28 days than at 7 days.

At 365 days of curing (Figure 7f), mixture CDW25+CKD10 showed a higher modulus than mixture CDW25+CKD20; similarly, CDW25+CEM2 presented a higher RM than CDW25+CEM4. These results confirm that such mixtures can be optimized in terms of binder content to obtain the maximum stiffness.

Figure 8 shows the effects of curing time for the same binder type and content on RM for CDW8 and CDW25 mixture types. Figure 8a shows that CDW stabilized with 2% of OPC does not exhibit significantly changed RM values when passing from 7 to 28 days. A significant increase, however, is evident at 365 days of curing. Conversely, when stabilized with 10% of CKD, the effects of curing time seem to be negligible (Figure 8b). In particular, the mixture exhibited a first decrease in RM passing from 7 to 28 days, followed by an increase when tested after 365 days with values similar to those measured after 7 days.

The evolution in RM over time of CDW25 combined with 2 and 4% of OPC is shown in Figures 8c and 8d. For these mixtures, the RM decreases slightly when passing from 7 to 28 days, while it increases passing from 28 to 365 days of curing. This fluctuating result could be attributable to changes in the cement matrix as a result of shrinkage-induced cracking phenomena, which develop mainly during the first four weeks, and the hydration-induced hardening phenomena, which may last for a long time beyond the standard term of 28 days.

The effects on RM following stabilization with CKD are illustrated in Figures 8e and 8f. It can be seen that the results accruing from the addition of 20% of CKD to CDW25 are inferior to those obtained with the addition of 10% of CKD. The oscillation in RM results over time in this case can also be linked with the effects of shrinkage and hydration from the binder phase.

In general, materials that exhibit a higher RM are able to distribute stress and strains in the pavement system that may help deeper layers to support the upper layers of the pavement, thus resulting in lower permanent deformations during the pavement life cycle. A greater stiffness may also contribute to a reduction in the thickness of layers, thus leading to a general cost saving.

To support the design of pavement structures containing the material investigated here, Table 5 provides the results of a calibration carried out by considering the generalized model proposed in the AASHTO (2015):

$$RM = k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \quad (5)$$

where θ is the bulk stress (equal to the sum of the three principal stresses), τ_{oct} is the octahedral shear stress, p_a is the normalizing stress assumed equal to the atmospheric pressure, and finally the three k parameters (k_1, k_2, and k_3) are the calibration factors obtained from the fitting of the RM test data. Their values are listed in Table 5 with the coefficient of determination R^2.

In the case of non-stabilized CDW aggregates, the parameter k_1, which is proportional to the Young's modulus, increases over time supporting the inference of the hardening effect of hydration of active components. This hydration process is possible thanks to the presence of free water in the samples that have been adequately stored in isolated conditions during the curing process. After

365 days, CDW8 exhibits a k_1 value that is 2.5 times higher than the value at 28 days, and 3.7 times higher than the value at 7 days.

The same coefficient for all the stabilized mixtures, with the sole exception of CDW25+CKD20, decreased passing from 7 to 28 days, and increased significantly passing from 28 to 365 days. This result supports the idea that after the mixing and compaction phases, the cement particles undergo a hydration process that leads to a contraction in volume and an increase in the space between particles. The hydration phase of the investigated stabilized mixtures is very slow, and in the long term it produces a significant increase in the k_1 parameter which roughly doubles in size passing from 28 to 365 days in the case of OPC stabilization, while it varies between 1.4 and 2.5 times in the case of CKD stabilization.

The k_2 parameter in eq. 5 is always positive, which means that CDW mixtures develop a hardening behavior when the bulk stress increases, in line with the behavior normally observed with unbound and stabilized granular materials for pavement applications. Finally, the k_3 parameter is nearly always negative, suggesting that materials exhibit a softening behavior in response to an increase in shear stress. Only in the cases of CDW8 and CDW25 at 7 days of curing did the regression of test data lead to a positive parameter.

In conclusion, the 0-25 mm recycled aggregates performed better when stabilized with OPC, while the 0-8 mm recycled aggregates worked better with CKD. However, the highest values of RM were recorded for the CDW8+CKD10 mixture, which probably represents the best combination from among those investigated here. It is worth noting that in this research the authors did not investigate the optimal combination of components, but rather the effects of specific CKD and OPC content levels in the mixtures. Therefore, the possibility that a CDW25 mixture with a different CKD content could have higher RM values should not be ruled out. Finally, all the stabilized mixtures show RM within the typical values of granular materials for subbase and base courses.

Properties at failure

Figure 9 exhibits the results of the stress at failure measured with the UCS test. It reports the data for the un-stabilized reference materials (CDW8 and CDW25) tested immediately after the compaction of samples (0 days) and for the three curing periods of 7, 28 and 365 days. It is worth noting that after a year of curing, CDW8 reached an UCS of 1.9 MPa from 0.2 MPa at 28 days. This can be explained by the formation of new bonds between grains due to the presence of free active oxides in the granular matrix.

Stabilized mixtures have been tested at 7, 28 and 365 days. The data confirm that the strength values increase over time, and the addition of 10% of CKD provides higher resistance than the addition of 20%, thus confirming what was previously observed in the case of RM test results, where the CDW25+CKD10 showed higher moduli than CDW25+CKD20.

In the case of OPC, the increase in cement content from 2 to 4% does not seem to have any effect on the strength properties of the stabilized mixtures. The addition of 4% of OPC has an effect only on the UCS measured after 7 days of curing.

Furthermore, the effects of the stabilization seem greater on the finer size gradation (0-8), while with CDW25 at 28 days of curing higher strength is associated with lower binder content (2% in the case of OPC, 10% in the case of CKD).

Table 6 reports the results for tangent and secant moduli, while Table 7 includes toughness and removability modulus. Results suggest that curing time and binder content tend to increase mixture stiffness with the exception of mixture CDW25+CEM4.

Curing time also contributes to an increase in mixture toughness. It is worth noting that in the case of CKD stabilization at 20%, the capacity of the material to absorb energy is reduced when compared to the mixture stabilized with 10% of CKD. Finally, the results obtained with the RE modulus confirm that a CKD stabilized mixture cannot be removed by means of excavation. After 365 days, the samples of CDW8 exhibited a RE significantly greater than 1, thus confirming that CDW is an evolutive material due to the presence of active elements whose stiffness and strength values change over time.

CONCLUSIONS

The paper presents the results of an experimental investigation aimed at the evaluation of construction and demolition wastes (CDW) which were characterized and tested for two different gradations (0-8 mm and 0-25 mm). These two classes were also stabilized with 10 and 20% by weight of cement kiln dust (CKD) with a view to obtaining materials usable in the formation of pavement subbases and subgrades. For comparison purposes, an ordinary Portland cement (OPC) was used as an alternative stabilizer. The most significant results are summarized as follows:

1. the mechanical properties of CDW-CKD stabilized mixtures are comparable with those of CDW-CEM ones albeit with a CKD content typically 5 times greater than the corresponding OPC content;
2. the temperature increment due to the exothermal reaction between CKD and water does not significantly affect moisture loss during the mixing process; this observation should be reassessed in full scale applications where the magnitude of moisture loss could be higher because of mass and surface effects;
3. the addition of CKD decreases the workability of CDW-CKD mixtures; , the workability of CDW25 with 20% of CKD is greater than CDW25 with 10% of CKD;

4. the resilient modulus of CDW-CKD mixtures increased significantly from the CDW sample starting values, reaching values which are typical for granular base courses made up of unbound granular materials;
5. CDW significantly enhances the mechanical properties of mixtures over time, as confirmed by tests carried out after 28 and 365 days of curing; active components are able to moderately increase their stiffness only if the materials maintain the moisture content levels present at the preparation stage;
6. the alternative use of CKD prevents the loss of stiffness exhibited by OPC in the transition from 7 to 28 days; it also guarantees an increasingly resilient behavior over time;
7. samples containing CKD tested at 7 days have resilient modulus values similar to those for samples tested at 28 days, leading to the conclusion that after 7 days the material has essentially matured;
8. after 365 days, all the CDW-CKD mixtures exhibit RM values slightly higher than those at 7 and 28 days of curing, while the compressive strength tends to double;
9. the addition of 20% of CKD to CDW25 does not improve RM and compressive strength values when compared to the mixture prepared with 10% of CKD; this could be due to shrinkage which can affect mixtures having higher amounts of CKD;
10. to avoid excessive cracking and to develop stiffness and strength, water loss should be prevented in both stabilized and non-stabilized CDW mixtures.

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Figures:

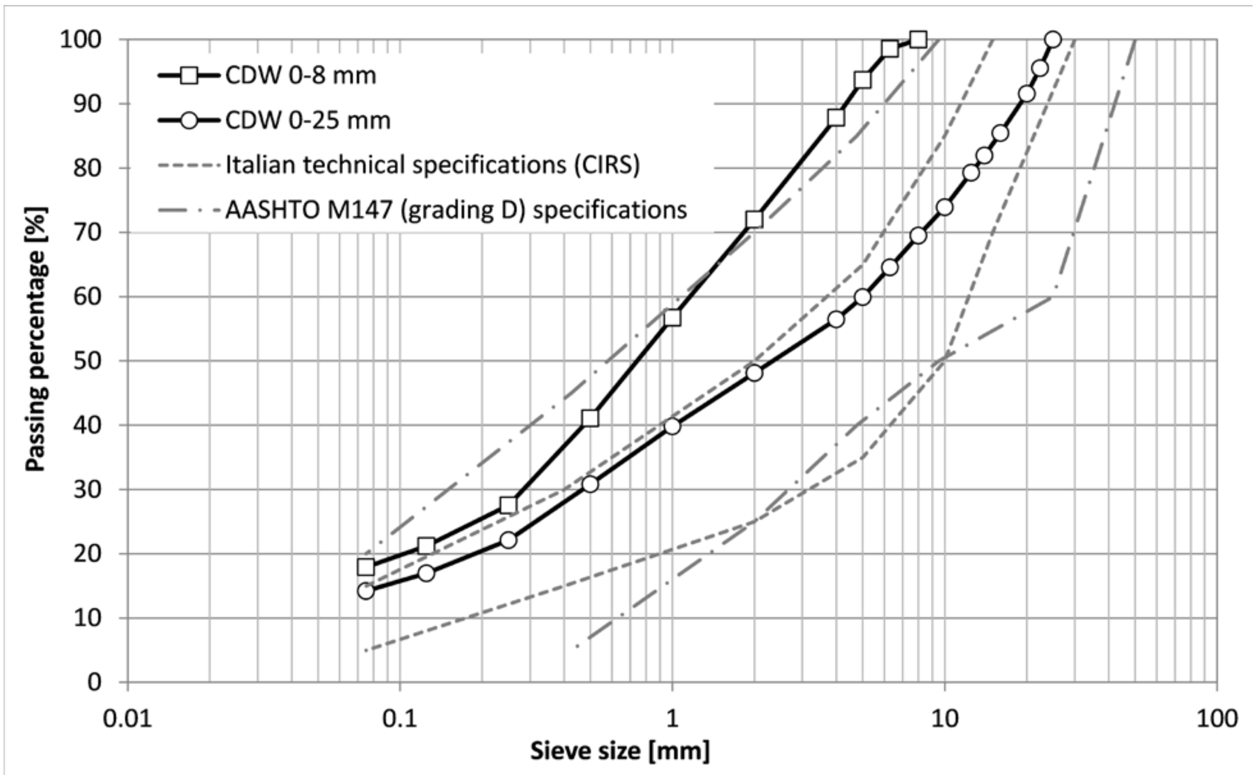


Fig. 1 Gradation of CDW employed

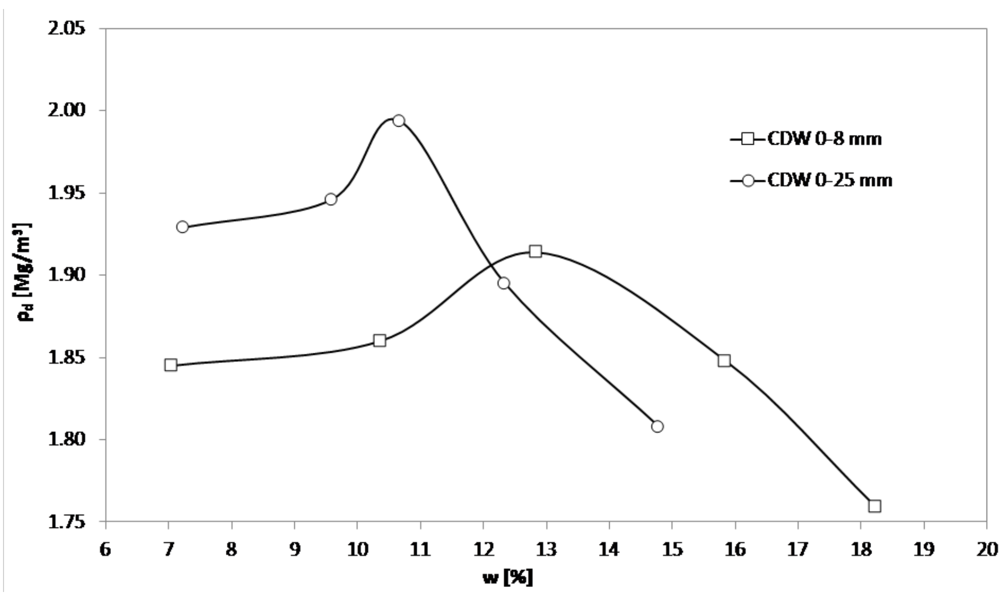
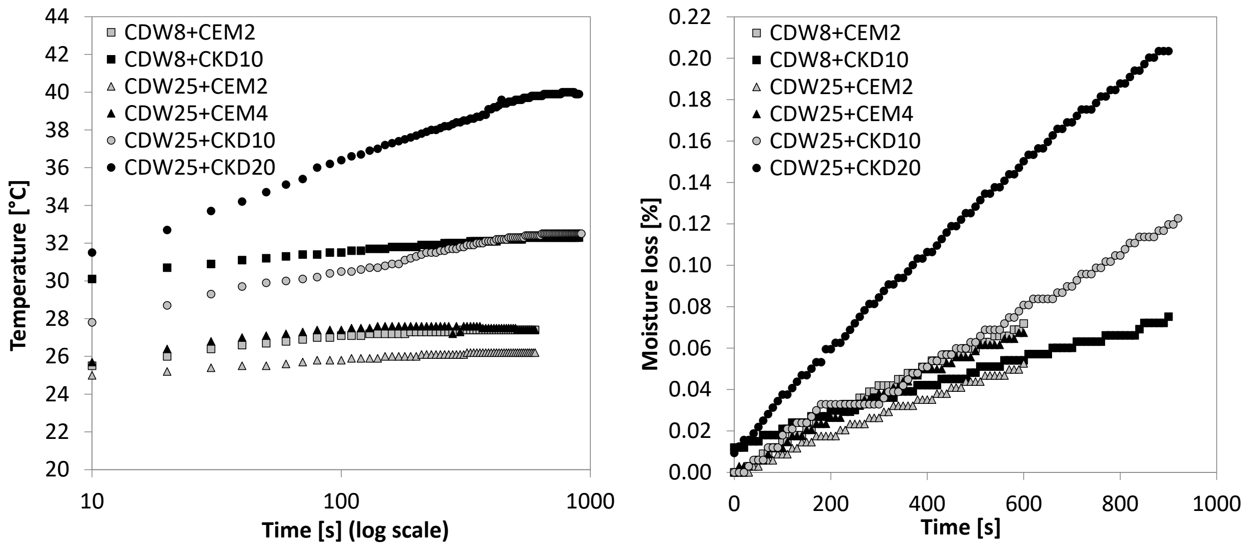


Fig. 2 Synthesis of Proctor study on the two CDW materials



(a) (b)

Fig. 3 Temperature monitoring (a) and moisture loss (b) during the hydration reactions

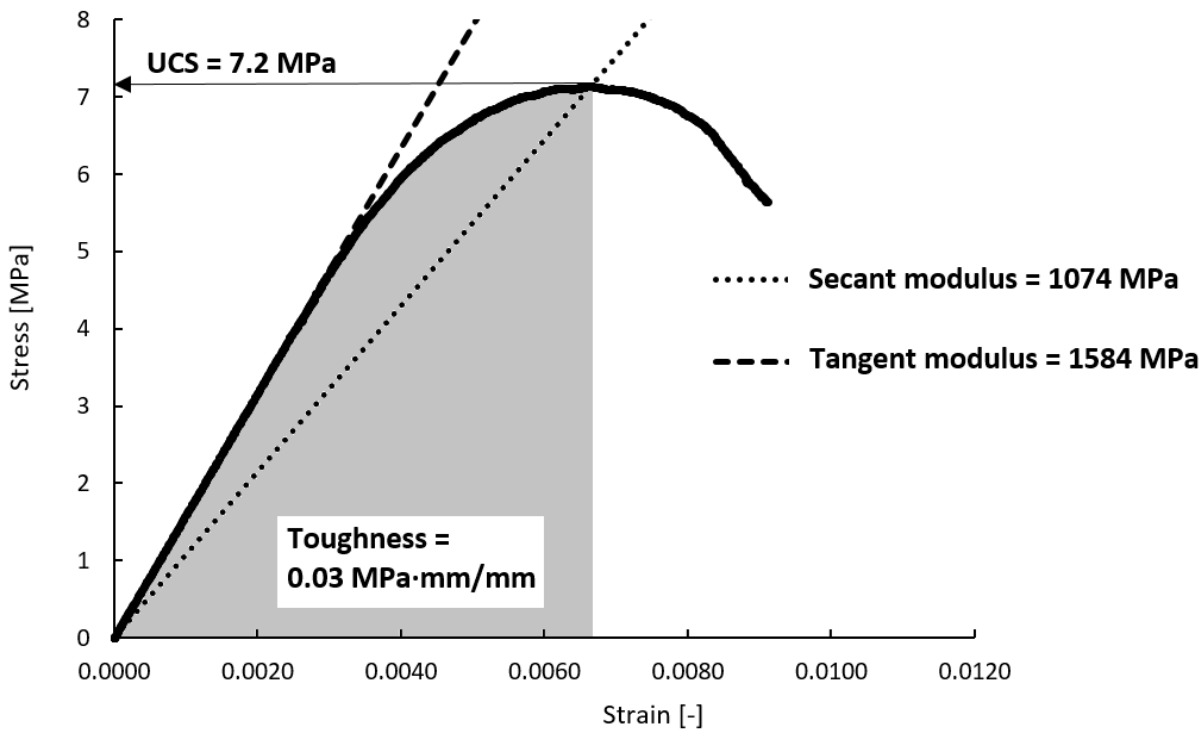


Fig. 4 Stress-strain curvilinear relationship with indication of secant modulus, tangent modulus and toughness (unconfined compression test on CDW8+CKD10, sample #1, at 365 days of curing)

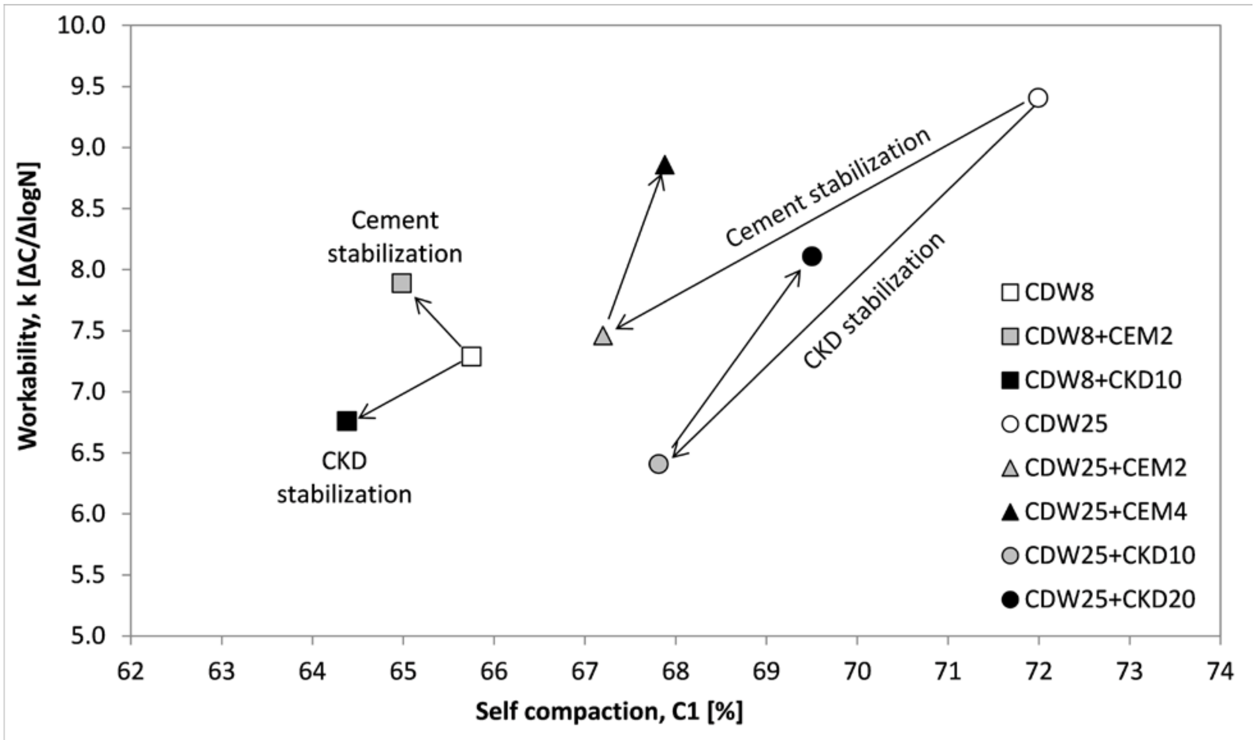
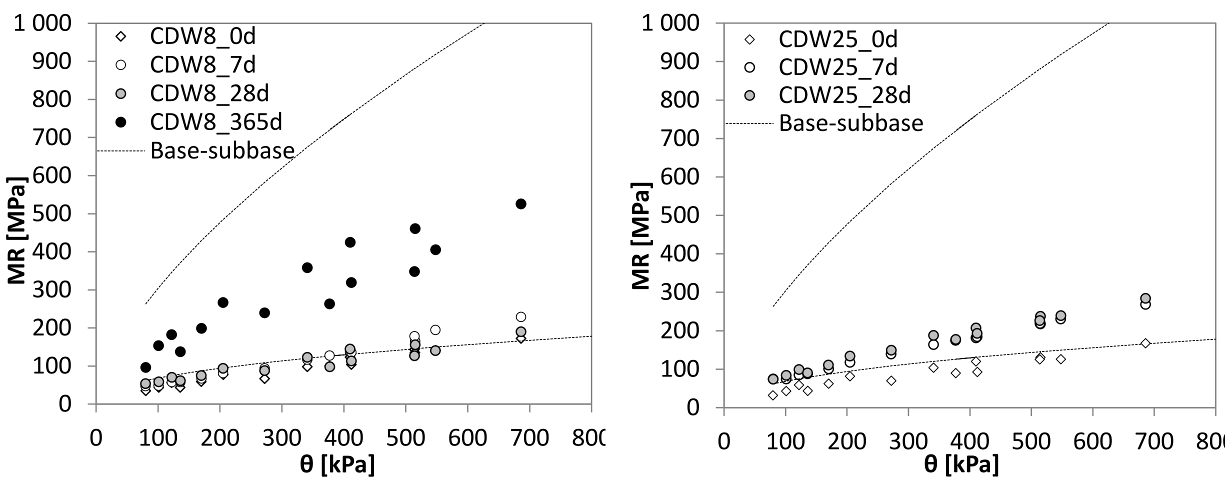


Fig. 5 Relationship between self-compaction (C_1) and workability (k) parameters



(a) (b)

Fig. 6 Resilient modulus test results as a function of the first invariant (θ) with reference limits for granular base and subbase materials. Comparison between curing time for mixtures CDW8 (a) and CDW25 (b)

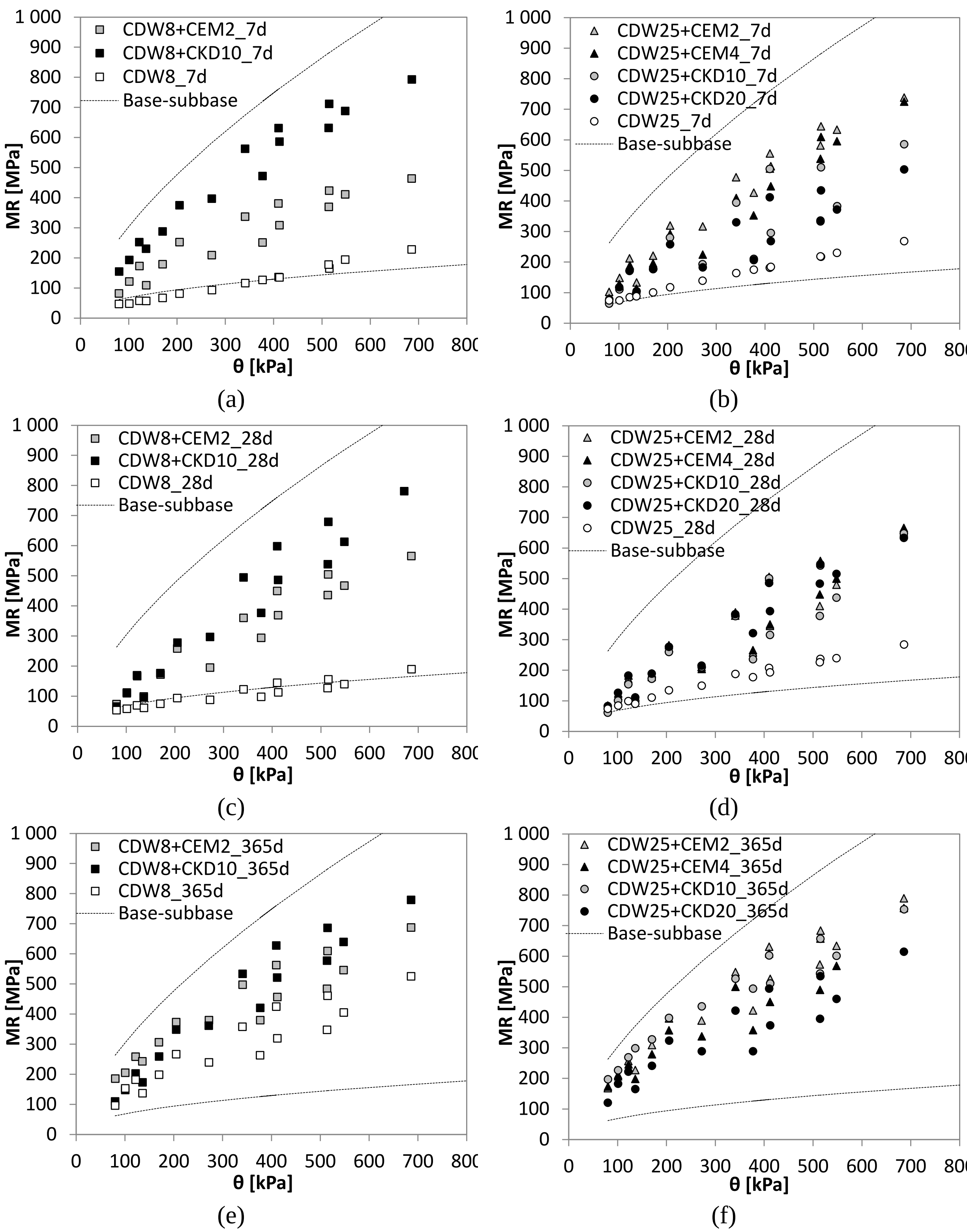


Fig. 7 Resilient modulus test results as a function of the first invariant (θ), and comparison with reference limits for granular base and subbase materials. (a) CDW8 mixtures at 7 days of curing; (b) CDW25 mixtures at 7 days of curing; (c) CDW8 mixtures at 28 days of curing; (d) CDW25 mixtures at 28 days of curing; (e) CDW8 mixtures at 365 days of curing; (f) CDW25 mixtures at 365 days of curing

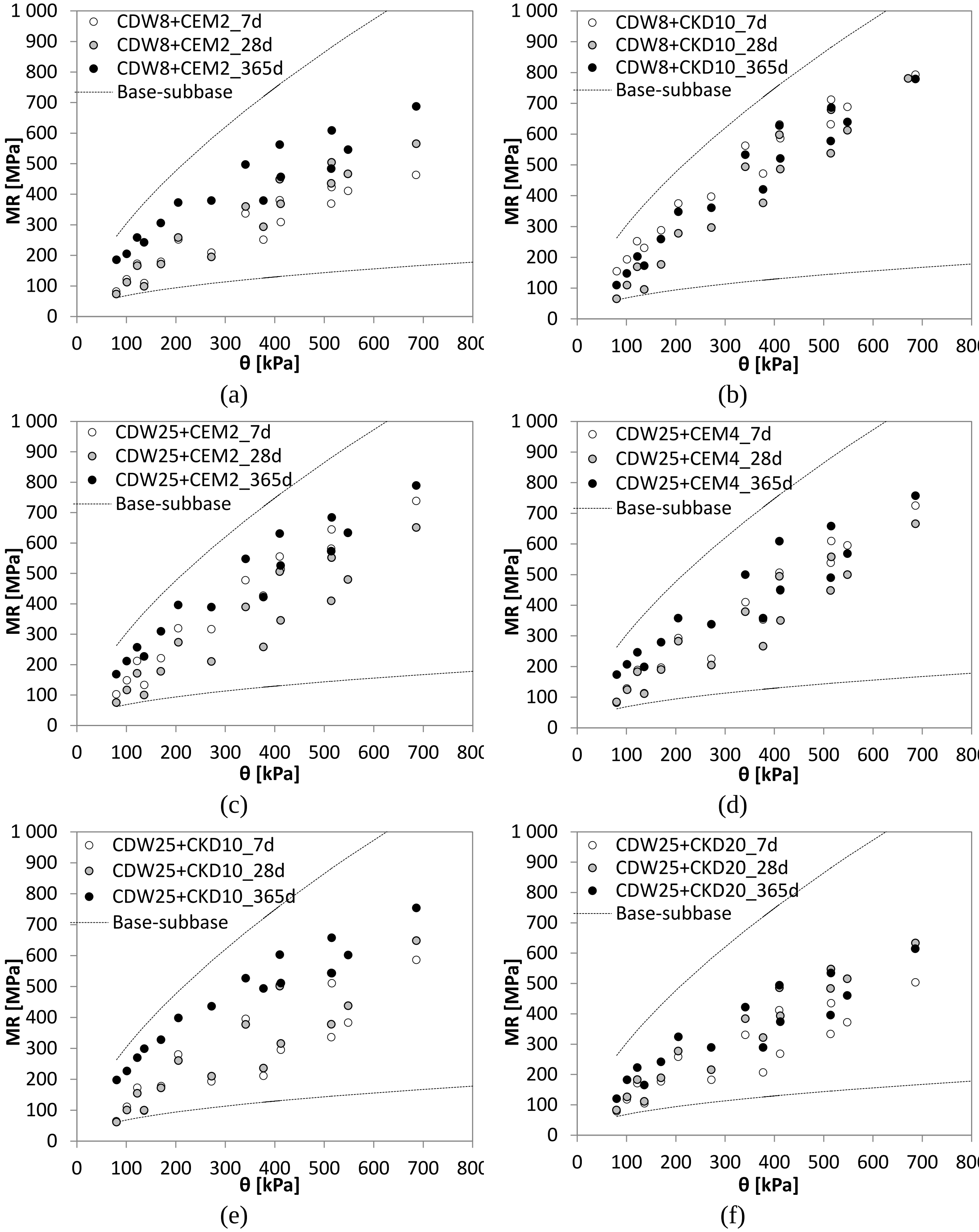
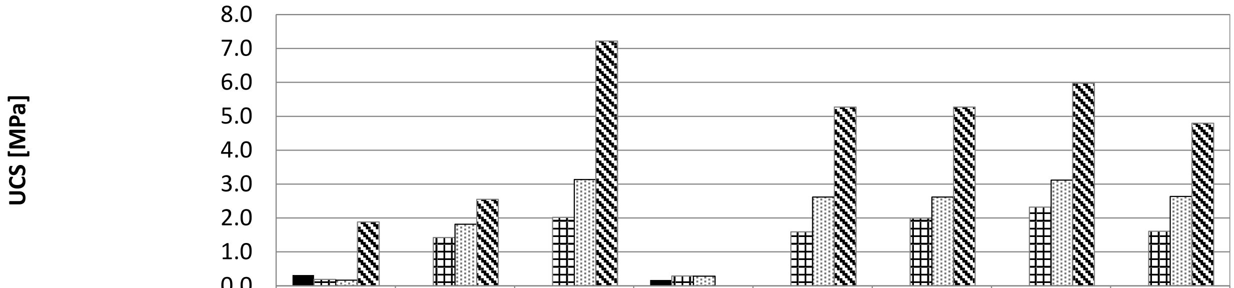


Fig. 8 Resilient modulus test results as a function of the first invariant (θ). Comparison between curing time for mixtures CDW8+CEM2 (a), CDW8+CKD10 (b), CDW25+CEM2 (c), CDW25+CEM4 (d), CDW25+CKD10 (e), CDW25+CKD20 (f)



	CDW8	CDW8 +CEM2	CDW8 +CKD10	CDW25	CDW25 +CEM2	CDW25 +CEM4	CDW25 +CKD10	CDW25 +CKD20
UCS [MPa] @ 0 days	0.3			0.2				
UCS [MPa] @ 7 days	0.2	1.4	2.0	0.3	1.6	2.0	2.3	1.6
UCS [MPa] @ 28 days	0.2	1.8	3.1	0.3	2.6	2.6	3.1	2.6
UCS [MPa] @ 365 days	1.9	2.6	7.2		5.3	5.3	6.0	4.8

Fig. 9 Unconfined compressive strength test results

Table 1 Physical properties of employed CDW

CDW	Particle density [Mg/m^3]	Flakiness Index (%)	Shape Index (%)
0-8	2.674	37	12
0-25	2.539	21	19

Table 2 Chemical oxide analysis and physical properties of binders

Binder type	CEM II/B-P 32.5 R	CKD
Al_2O_3 (%)	3.5	3.8
CaO (%)	60.9	47.0
Fe_2O_3 (%)	2.6	2.2
K_2O (%)	0.8	1.9
MgO (%)	1.8	0.9
Na_2O (%)	0.2	0.3
P_2O_5 (%)	-	0.05
SO_3 (%)	2.4	1.5
SiO_2 (%)	15.1	12.9
TiO_2 (%)	-	0.2
Cl^- (%)	0.06	0.8
Loss on Ignition (LOI, %)	12.4	28.4
Passing (%) at 40 mm sieve	98.0	77.6
Passing (%) at 24 mm sieve	83.7	57.0
Passing (%) at 8 mm sieve	43.7	23.0
Volumetric stability (mm)	0	-
Initial setting time (min)	150	> 1440
Final setting time (min)	270	> 1440
Flow (mm)	95	0
Density (kg/m^3)	2900	2700
Specific surface (cm^2/g)	3700	5000
Unconfined compressive strength (MPa) and percentage of UCS @ 28 days:		
1 d	12.9 (31.7%)	-
2 d	21.2 (52.1%)	-
7 d	-	1.0 (33%)
28 d	40.7 (100%)	3.0 (100%)

Table 3 Synthesis of the investigated mixtures

Mixture designation	Aggregate type	Binder type	Binder dosage[(a)] (%)	OMC[(b)] (%)	$\rho_{d,max}$ [Mg/m^3]	# of replicates
CDW8	CDW 0-8 mm	-	-	12.8	1.914	4
CDW8+CKD10	CDW 0-8 mm	CKD	10	14.4	1.850	8
CDW8+CEM2	CDW 0-8 mm	OPC	2	13.3	1.876	8
CDW25	CDW 0-25 mm	-	-	10.7	1.994	4
CDW25+CKD10	CDW 0-25 mm	CKD	10	12.3	1.894	8
CDW25+CKD20	CDW 0-25 mm	CKD	20	13.9	1.786	8
CDW25+CEM2	CDW 0-25 mm	OPC	2	11.2	1.952	8
CDW25+CEM4	CDW 0-25 mm	OPC	4	11.7	1.948	8

NOTE: CDW = construction and demolition waste; CKD = cement kiln dust; OPC = ordinary Portland cement
[a] by total weight of dry aggregates
[b] by total weight of dry aggregates plus binder

Table 4 Compaction and density parameters of mixtures

Mixture designation	k [ΔC/ΔlogN]	C_1 [%]	N@ $\rho_{d,max}$
CDW8	7.29	65.8	85
CDW8+CKD10	6.76	64.4	101
CDW8+CEM2	7.89	65.0	84
CDW25	9.41	72.0	43
CDW25+CKD10	6.41	67.8	84
CDW25+CKD20	8.11	69.5	33
CDW25+CEM2	7.46	67.2	73
CDW25+CEM4	8.86	67.9	41

Table 5 Synthesis of the eq. 5 calibration for the investigated mixtures according to the M-EPDG model (AASHTO 2015)

Mixture designation	Curing time	k_1	k_2	k_3	R^2
CDW8	0 d	394	0.84	-0.34	0.92
	7 d	423	0.70	0.59	0.98
	28 d	576	0.38	-1.60	0.82
	365 d	1457	1.23	-2.26	0.96
CDW8+CEM2	7 d	1287	1.11	-1.64	0.87
	28 d	1160	1.31	-1.78	0.85
	365 d	2335	1.00	-1.78	0.86
CDW8+CKD10	7 d	2977	0.84	-1.21	0.98
	28 d	1254	1.56	-2.25	0.91
	365 d	1778	1.27	-1.86	0.92
CDW25	0 d	425	0.99	-1.19	0.96
	7 d	725	0.61	0.24	0.78
	28 d	824	0.75	-0.46	0.78
CDW25+CEM2	7 d	1565	1.12	-1.10	0.95
	28 d	1117	1.66	-2.88	0.83
	365 d	2240	1.09	-1.70	0.96
CDW25+CEM4	7 d	1205	1.26	-1.23	0.96
	28 d	1139	1.51	-2.33	0.90
	365 d	2014	1.25	-2.29	0.92
CDW25+CKD10	7 d	1991	1.26	-3.02	0.83
	28 d	1014	1.84	-3.44	0.83
	365 d	2556	0.88	-1.29	0.96
CDW25+CKD20	7 d	1192	1.47	-2.88	0.91
	28 d	1235	1.28	-1.60	0.94
	365 d	1790	1.23	-2.40	0.82

Table 6 Secant and tangent modulus values

Mixture designation	Secant modulus [MPa]				Tangent modulus [MPa]			
	0 days	7 days	28 days	365 days	0 days	7 days	28 days	365 days
CDW8	30.8	30.5	35.7	180.0	36.3	42.1	49.7	215.2
CDW8+CEM2	-	104.0	167.4	212.0	-	124.1	282.8	370.4
CDW8+CKD10	-	216.6	361.3	888.0	-	309.9	576.8	1255.7
CDW25	11.2	45.5	35.0	-	13.0	61.1	52.4	-
CDW25+CEM2	-	133.2	306.0	441.8	-	184.5	431.0	594.0
CDW25+CEM4	-	143.6	385.2	505.1	-	225.3	590.0	625.4
CDW25+CKD10	-	330.0	423.5	766.5	-	478.1	574.4	985.3
CDW25+CKD20	-	237.4	440.5	724.9	-	334.7	550.5	864.1

Table 7 Toughness and Removability modulus values

Mixture designation	Toughness [kPa·mm/mm]				Removability modulus [-]		
	0 days	7 days	28 days	365 days	7 days	28 days	365 days
CDW8	1.9	0.7	0.5	11.3	0.8	0.8	2.7
CDW8+CEM2	-	11.2	12.6	19.6	2.3	2.6	3.0
CDW8+CKD10	-	11.8	17.7	37.7	2.6	3.3	5.0
CDW25	1.5	1.1	1.5	-	1.1	1.1	-
CDW25+CEM2	-	11.8	12.8	26.9	2.5	3.1	4.1
CDW25+CEM4	-	17.4	11.6	32.2	2.8	3.2	4.5
CDW25+CKD10	-	10.3	13.9	28.3	2.9	3.3	4.6
CDW25+CKD20	-	6.8	9.2	18.4	2.3	2.9	3.9