

RECYCLED SAND FROM BRAZILIAN CONSTRUCTION AND DEMOLITION WASTE

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ABSTRACT

The existing construction waste recycling technologies and standards have been long applied in construction and demolition (C&D) waste recycling, but it is essentially focused on the production and use of coarse recycled aggregates. Very few papers focus on the production of recycled sand although some previous results show that fine aggregates fraction (below 4.8mm) represents around 40 to 60% (in mass) of the Brazilian waste and it is usually downcycled as road sub-base or disposed in landfills. The quality of the recycled aggregate is strictly related to the content of porous and low strength phases, as the patches of cement attached to the recycled aggregate. Despite being the crucial factor for aggregate performance, the removal of adhered cement paste is not a simple task. Some technologies have already been described in the literature, even though, to the moment none of these technologies has clearly succeeded in reaching the large market available. This paper presents a summary of the main properties of the sand produced from C&D waste by VSI attrition and abrasion comminution. The main properties of recycled aggregates are discussed and compared to the previous C&D waste, respectively: apparent density, water absorption, chemical composition, porosity, particle shape and cement paste content.

KEYWORDS

Recycled sand, construction and demolition waste recycling, mineral processing, crushing

INTRODUCTION

The composition of construction and demolition waste (CDW) is dictated by different construction types and their components but in general it is concrete, asphalt, brick and ceramics (Hong *et al.* 2008). The problems related to dumping waste have critically increased with the growing and development of big cities. In the UK, for example, over 50% of waste in landfills come from construction (Vivian *et al.* 2008) and USA alone generates around 200 to 300 million tons of CDW annually (Meyer 2009). The exhaustion of natural sand deposits close to large urban centres is another portion of the CDW problems.

Previous studies showed that about 50% weight of the product generated in the comminution of recycled aggregates corresponds to the fine fraction (particles below 4.8 mm) (Ulsen *et al.*, 2009). For too long the fine fraction was disregarded or used as road base pavement because of the belief of its low quality properties; regardless of any limitations that may exist, the use of recycled aggregates in concrete shall be essential in the near future (Cachim 2009). However, recent studies have shown that the fine fraction properties are not so different from the coarse fraction and it can be improved with the appropriated processing (Muller *et al.* 2005). Experimental tests showed the viability of partial replacement of natural sand by crushed bricks in mortar production (Moriconi *et al.* 2003; Cachim 2009).

The quality of the recycled aggregate is strictly related to the content of porous and low strength phases, as the patches of cement that remain attached to the recycled aggregate. This phase accounts for the increase in water absorption, which prolongs the mixing time and affects the strength of the recycled aggregates (Cachim 2009), in particular for replacement of virgin aggregates over 15 to 20% of coarse (Cachim 2009) or fine aggregates (Poon *et al.* 2007).

Specific surface area directly influences the water demand and consequently increases the cement consumption, for a set water/cement ratio (Vivian *et al.* 2008). Otherwise, keeping the same cement ratio, the free water in cement paste rises and then there is an increase in the porosity (Cachim 2009). Krus *et al.* (Krus *et al.* 1997) explained this by considering the fact that water is a strong polar liquid, thus it can slip between the mineral layers of the cement paste, widen up the distances between them, allowing further new pore spaces.

Despite being the crucial factor for aggregate performance, the removal of adhered cement paste is not a simple task. The literature shows that it can be carried out by successive comminution stages (Nagataki *et al.* 2004), thermal treatments (Ahn 2001; Shima *et al.* 2005) or electrical discharge (Kiss *et al.* 1980; Linsz *et al.* 2004). However, so far, none of these technologies has actually managed to reach the large market available.

Mineral processing has been long applied to CDW recycling, although few authors focus on the production of recycled sand. The production of sand from crushed stone (artificial sand) has been carried out for over a decade by vertical shaft impactors (VSI). The equipment consists of a rotor revolving at high speed; the rotor throws the material centrifugally within the crushing chamber where the comminution occurs by rock-on-rock impact, attrition and abrasion (Wills 2006). The main advantage of the VSI crusher is the production of cubic particles in all fraction sizes which provides more quality to the sand and to the concrete (Tomas *et al.* 2000; Bengtsson *et al.* 2006).

Regarding the use of VSI, some operational advantages deserve to be mentioned: control of the product size distribution by rotor rotation (Bengtsson *et al.* 2006), low cost of labour, it does not crush the fines and it consumes 6% less energy than the conic crusher to the same feed rate (Lindqvist 2008). The rotation (rotor speed) is the parameter that most influences the particles shape, size distribution and porosity of aggregates (Bengtsson *et al.* 2006).

The selective removal of the cement paste attached to recycled aggregates by a vertical impact crusher and the potential improvement in the quality of the recycled sand produced are investigated. The main properties of recycled aggregates are discussed and compared to the previous C&D waste.

EXPERIMENTAL

Sampling

The investigation was carried out on C&D waste from "Urbem Tecnologia Ambiental" a private recycling plant, located in the city of Sao Bernardo do Campo, Sao Paulo metropolitan area, Brazil. The composition of the waste is basically low-strength concrete (around 80%) and masonry.

The operational flowsheet of the plant is summarized in Figure 1a. It consists of a vibrating grizzly to remove the fraction below 4.8 mm before crushing (C&D sand fraction); comminution by impact crusher, magnetic separation to remove the remaining steel bars and, finally, a two-deck screen to perform the dry sieving and grading the products into three size fractions: <6.3mm, 6.3 to 39 mm and 39 to 150 mm. The organic materials, such as paper, wood, plastic and others are removed from the mineral fraction by hand sorting, either before or after crushing.

The sampling procedure was replicated twice a week for 60 days randomly selected. The samples were collected at the four product stock piles, in the same proportion as they are produced (2:5:2:3 as shown in the flowsheet). An average sample of the head sample (feed) was composed by mixing all aliquots (Urbem CDW). The total mass collected was about 4.000 kg.

The laboratory procedure is shown in Figure 1b and described below.

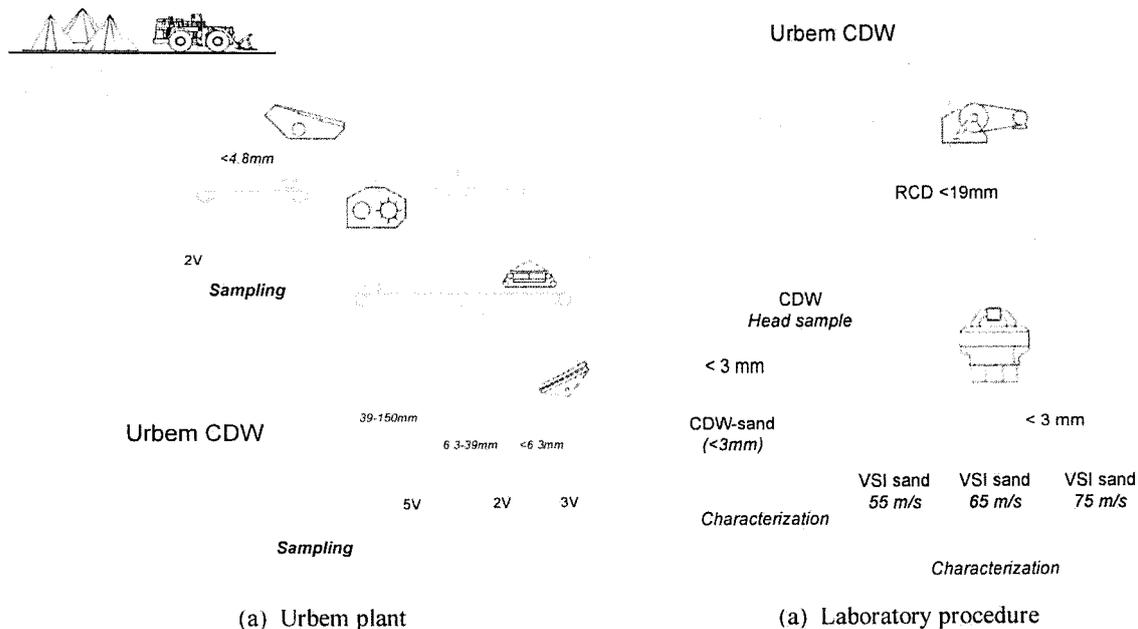


Figure 1 Flowsheet of Urbem recycling plant and sampled products (a); laboratory procedure (b)

Crushing

The total sample was comminuted in a laboratory jaw crusher in closed circuit to obtain a product below 19 mm (3/4"). This product was homogenized by horizontal elongated piles (Petersen *et al.* 2005) and a secondary sampling was performed for the attainment of three representative and equal aliquots. Each aliquot below 19 mm was crushed by a vertical shaft impact crusher (VSI) in closed circuit at a constant feed rate in three different rotor speed conditions (55, 65 and 75 m/s) to produce crushed sand from C&D waste. The tests were conducted on model Barmac 3000 at the pilot plant of Metso Brazil - Sorocaba, state of Sao Paulo.

Products characterization

The characterization procedure was conducted on the head sample (<math>< 19\text{mm}</math>), fraction below 3 mm of the head sample (CDW-sand) and on the VSI products.

The main parameters characterized were particle size distribution, particle shape, chemical composition, cement paste content, distribution in density classes from heavy liquid separation, water absorption, specific surface area and porosity. The aim of the products characterization is to compare the main properties of the recycled sand with the previous C&D waste.

The particle size distribution was determined by wet sieving to achieve more precise results. The objective was to appraise the VSI conditions and the amount of fines generated below 0.15 and 0.074 mm and also compare to the original sand fraction from CDW.

The particles shape were evaluated by dynamic image analysis on QICPIC real time particle analyzer to appraise the influence of the attrition and abrasion crushing on particles sphericity as well as to compare the effect of the rotor speed.

The chemical composition was determined by quantitative X-ray fluorescence in fused beads and the loss on ignition was assayed at 1,050°C.

The distribution in density classes was performed by heavy liquid separation. The procedure consists in placing a sample in an organic liquid with a high density the light particles float and the heavy particles sink, therefore separate particles with different porosity and oven-dry density, which influences the mechanical properties of the aggregates (Angulo *et al.* 2009b).

The measurement of the water absorption for fine aggregates is usually performed according to ASTM C 129. However, the standard method has long been criticized since the remains of cement paste affect the results of experiments which were designed for ordinary natural aggregate (Vivian *et al.* 2008). Hence, the water absorption was measured according to the methodology proposed by (Daminelli 2007). This methodology consists in saturating the pores with water using a vacuum system and then drying the sample using a microwave; the loss of weight has to be measured constantly. The graph of the drying rate versus time and the drying rate versus moisture allows the determination of the parameters to calculate the water absorption, such as dry mass, saturated surface dry mass and mass under water.

Scanning electron microscopy (SEM; Quanta 600 FEG) coupled to energy disperse spectrometer (EDS; Bruker Quantax) were used to characterize the phases association through backscattered images and X-ray digital mapping of the major elements (Si, Al, Fe, Na, K, Ca).

RESULTS AND DISCUSSIONS

Effect on particle size distribution

The particle size distributions of the characterized products are shown in Figure 2.

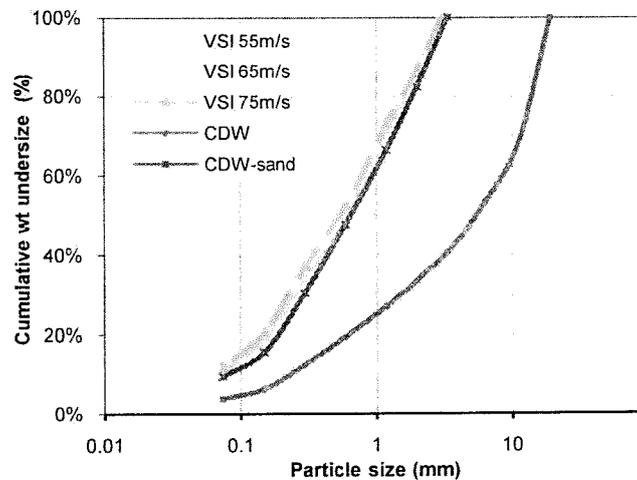


Figure 2 Particle size distribution of each product

The CDW head sample represents the aggregates after the second crushing stage on a recycling aggregate plant. This product has around 50% weight below 4.8 mm (sand fraction), of which 6% is below 0.15 mm. The CDW-sand (fraction below 3 mm from the head sample) indicates that 15% weight is below 0.15 mm.

The comminution of the CDW head sample on vertical shaft impactor (VSI) in three different rotor speeds produced sand with similar grading, with a subtle decrease in fine fraction percentage for the lowest speed. Furthermore, the tertiary crushing did not noticeably increase the amount of fines, so it can be concluded that the sand produced by tertiary crushing at VSI has quite a similar size distribution to that of the CDW-sand fraction.

Shape analysis

The results of shape analysis of VSI products and CDW-sand fraction are summarized by the frequency of particles with certain EQPC (diameter of a circle of equal perimeter) for each class of sphericity. Comparative results are shown in Figure 3.

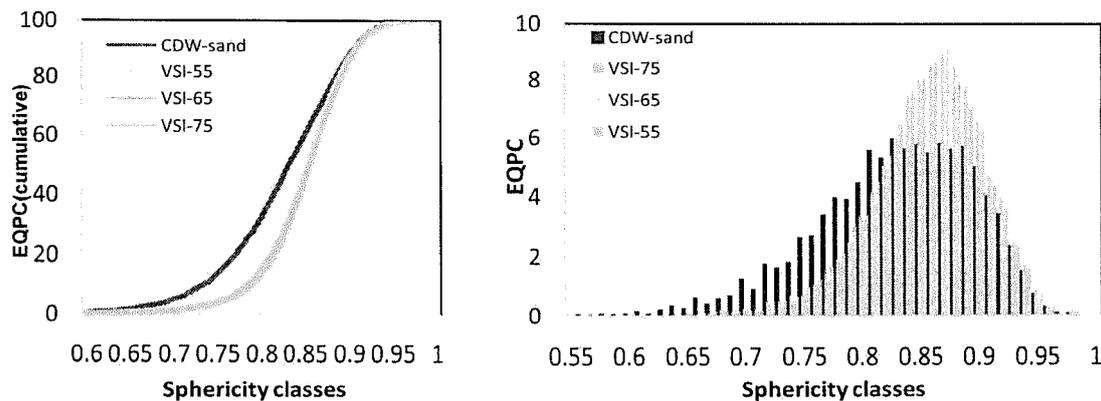


Figure 3 Sphericity classes of recycled sand from CDW

The effects of rotor speed on recycled sand are very subtle, since the sphericity of particles for the three crushing conditions is very similar. On the other hand, the sphericity of CDW-sand is rather different from the VSI crushed sand. In conclusion, the rock-on-rock crushing improved the morphology of recycled sand, when compared to the morphology of sand fraction from C&D waste. However, the rotor speed did not have great influence on particles shape.

Chemical composition of the main oxides

The composition of fractions above 0.15 mm of the recycled aggregates is represented mainly by silica (65-75%), calcium oxide (7-11%), alumina (6-10%) and iron oxide (around 2.5%). Loss on ignition is around 6 to 9%, in average. Minor compounds are Na_2O (0.5-2%), K_2O (1.5-3%) and MgO (1-2%). The sum of SiO_2 , Al_2O_3 , Fe_2O_3 , CaO and LOI grades surpass 90%.

The sum of silica, alumina and iron oxide grades can be correlated to the content of silicates from natural rock phases, sand and ceramics while the sum of the grades of calcium oxide and loss on ignition is directly related to the binder content (Angulo *et al.* 2009).

The comparative analysis of the content and distribution of $\text{CaO}+\text{LOI}$ for fractions above 0.15 mm for each product is shown in Figure 4. Distribution means the proportion of some compound in such a fraction or product in relation to the total content in the whole sample.

In this sense, almost 90% of the total content of $\text{CaO}+\text{LOI}$ is presented at a fraction above 0.15 mm for the CDW head sample, while the sand fraction for the same product represents 87% of the total $\text{CaO}+\text{LOI}$. For VSI crushed sand the amount of the same phase is reduced to values from 67.6% to 62.5%, for the same fractions.

These results are consistent with the previous one and show that the cement paste concentrates at the fine fractions. Moreover, the distribution curve decreases more abruptly than the mass distribution, indicating enrichment of cement paste for fine fractions. The crushing rotor speed did not have a crucial influence on chemical composition; the results for the three speed rotor test were quite similar.

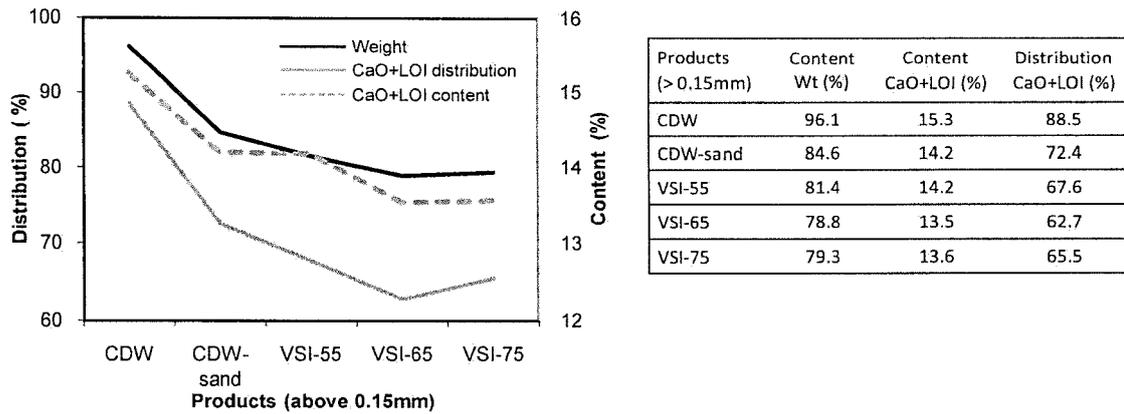


Figure 4 Comparative weight and CaO+LOI content and distribution

The relative behaviour of cement paste (Angulo *et al.* 2009) is indicated by ratio between the sum of the major oxides $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ and the sum of $\text{CaO} + \text{LOI}$, which means the higher the ratio, the lower the content of cement paste (Figure 6a – CDW head sample and Figure 6b – sand).

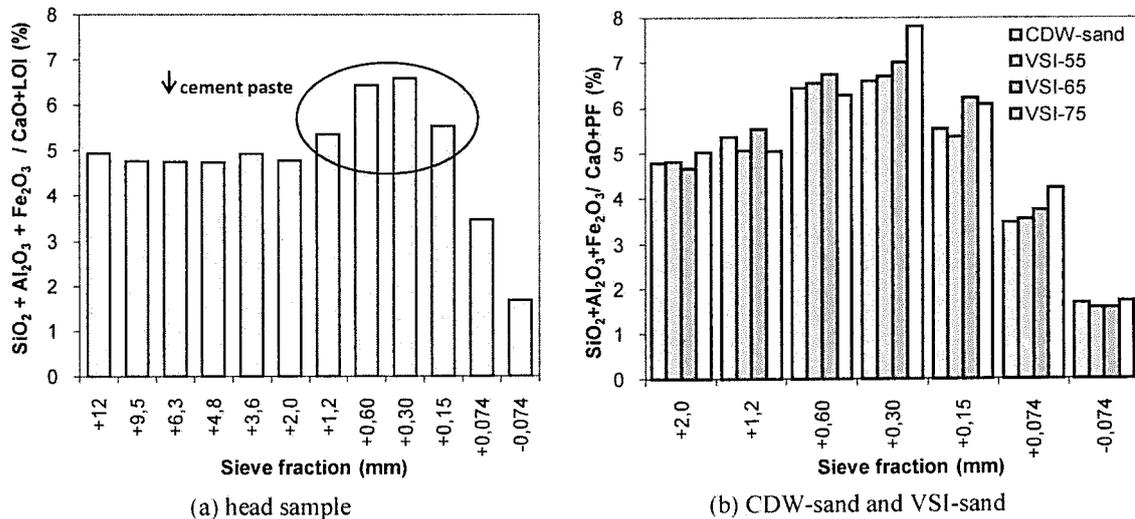


Figure 5 Correlations between the main oxides of CDW and recycled sand

According to these results, the coarse fraction of CDW (above 4.8mm) has higher content of cement paste than the fine fractions (Figure 6a). For fractions below 3 mm it is noticed a tendency on decreasing the cement paste content, mainly on fractions between 0.60 and 0.15 mm (Figure 6b), for both CDW-sand and VSI-sand.

The comparison between the ratio $\text{SiO}_2 / (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$ is presented in Figure 6. This correlation indicates the content of quartz compared to the aluminum silicates (mainly feldspars) from natural aggregates (essentially granites).

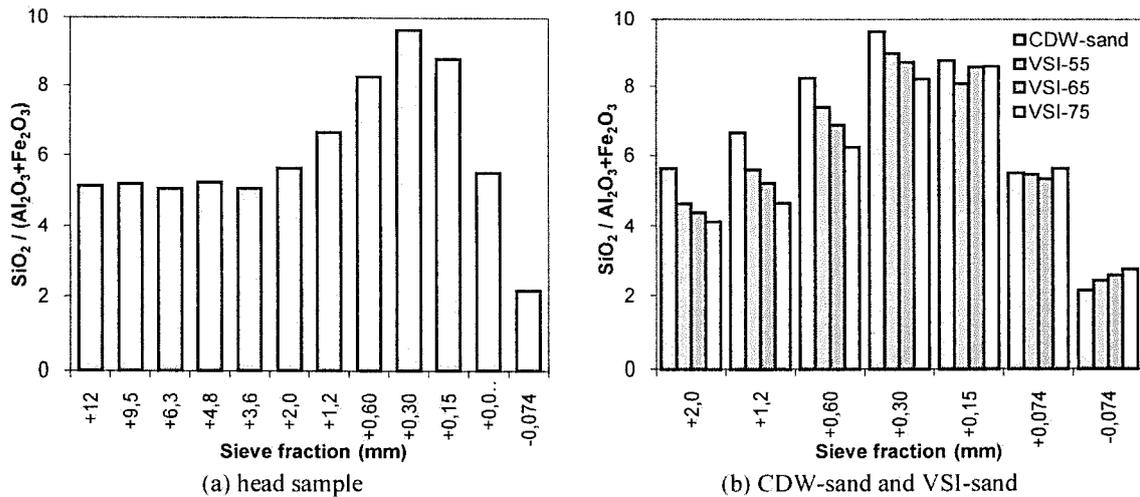


Figure 6 Correlations between quartz and aluminum silicates of CDW and recycled sand

The results from Figure 6 indicate a natural increase of quartz in sand fractions. The increase in alumina and iron grades in VSI-sand in comparison to the CDW-sand demonstrates that crushed sand incorporates the aluminum silicates in the comminution process.

In conclusion, the content of cement paste diminishes in fraction below 1.2 mm and above 0.15 mm (Figure 5). The increase of cement paste content is also noticeable for fractions below 0.15 mm and even more evident below 0.074 mm, indicating that the cement paste tends to concentrate on the finest fraction sizes. The crushing step also leads to an increase in feldspars content for VSI-sand

Density separation

The comparative weight percentage of the sink products from the mineral separation in density 2.60 g/cm³ for size fraction above 0.15 mm is shown in Figure 7a while the comparative grades and distribution of CaO+LOI for these products are exposed in Figure 7b.

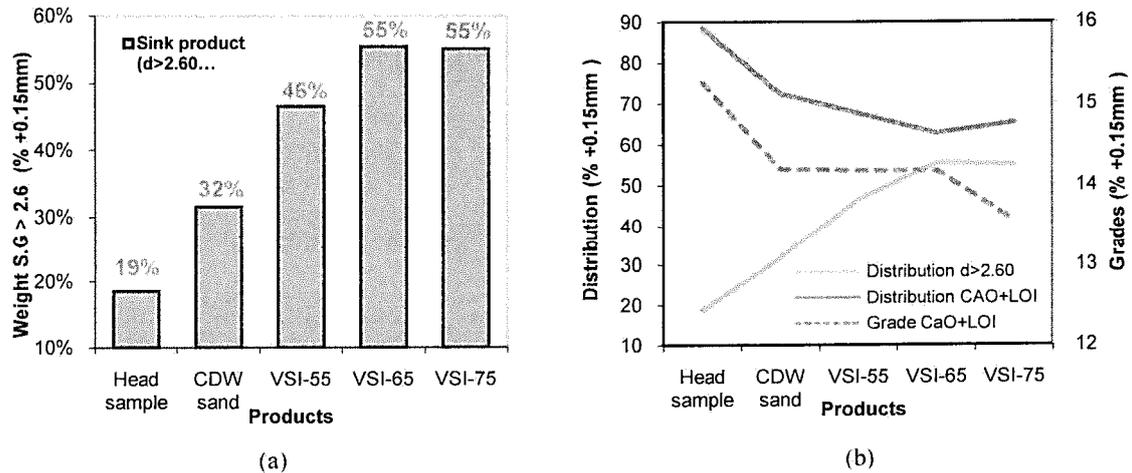


Figure 7 Weight percentage of sink product (a); weight of sink product at S.G 2.6, associated content and distribution of CaO+LOI (b)

The results of the heavy liquid separation clearly demonstrate that the head sample presents low content of sink fraction, which means that particles are more porous, and they are not thus properly liberated from the cement paste. The high grades of CaO+LOI corroborate this statement (Figure 7b). Comparatively, the CDW-sand fraction (<3 mm) originally present in the CDW head sample presents a higher amount of high density fraction and lower grade of CaO+LOI, also indicating a lower content of cement paste for each sieve fraction.

The results of sand from tertiary crushing compared to CDW show that liberation of cement paste is improved by VSI comminution. Besides, the increase in the rotor speed of the impact crusher from 55 to 65 m/s reduces the content of porous phase and thus rises the distribution of the materials in the sink product (density separation of 2.60 g/cm³). However, increasing the speed from 65 to 75 m/s did not improve the quality of the product in terms of envelop density, not even for the distribution of CaO+LOI.

Moreover, the density distribution in high density products increases for the fine fractions, as shown in Figure 8. Again, this confirms the fact that the liberation of cement paste improves for the fine fractions with a decrease in the porous phase fraction.

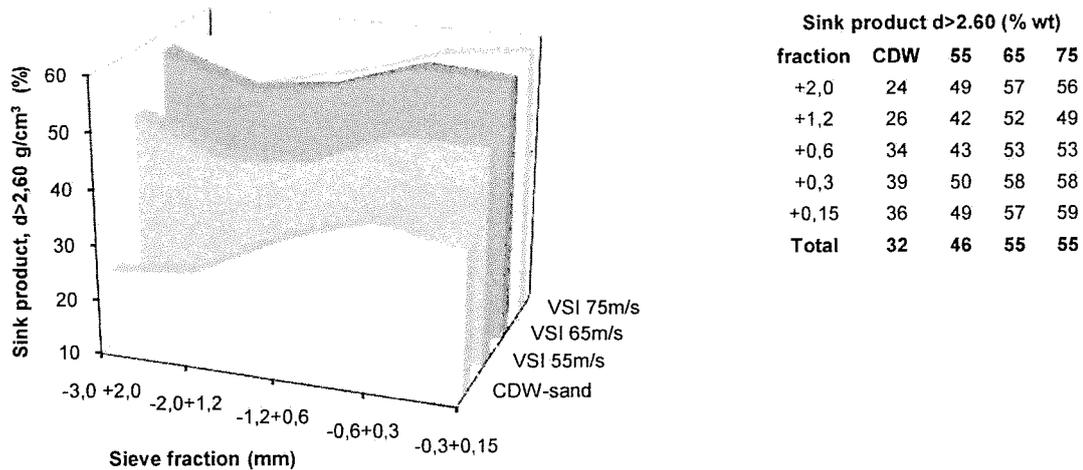


Figure 8 Weight percentage of high density products, for each size fraction

Water absorption and porosity

The comparative porosity and water absorption values for each studied sand are shown in Figure 9.

The water absorption obtained from the vacuum system are higher as compared to the standards method (Damineli 2007), since the water is forced to penetrate in smaller or less accessible pores, hence these values are not comparable to the water absorption values assayed by international standards. Apart from that, the comparative results are very comprehensible.

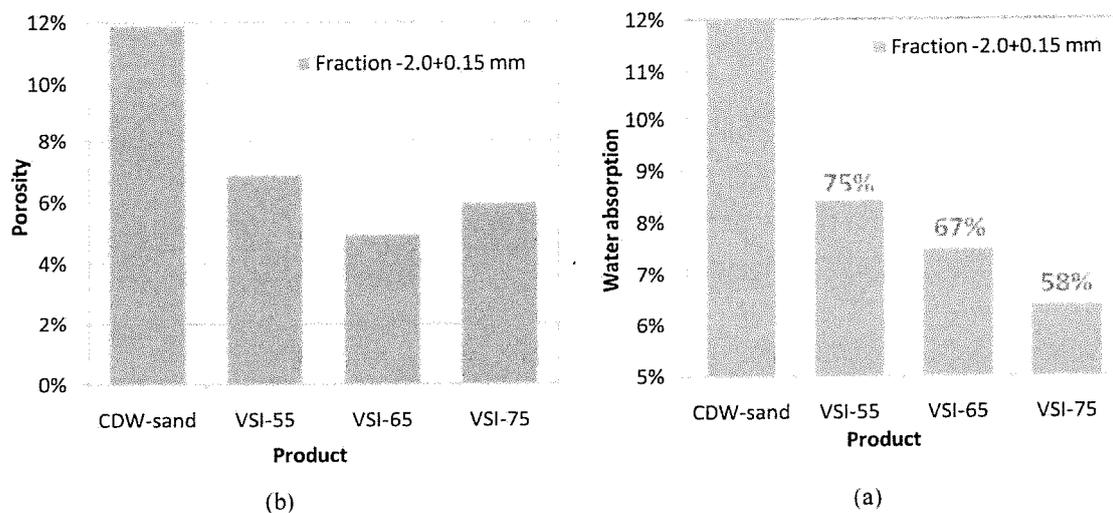


Figure 9 Comparative porosity and water absorption

The sand produced by VSI crushing clearly demonstrates the decrease in water absorption values (Figure 9b), therefore indicates the decrease of the porous phases. The crushed sand from vertical shaft impactor presented a reduction in water absorption varying from 75% to 58%, for different comminution conditions, as compared to the original sand present in the reference C&D waste. Besides, the porosity from CDW-sand fraction is almost the double of the porosity of VSI-sand.

In conclusion, the crushing step contributes to the production of low-porosity recycled sand.

Scanning electron microscopy

Comparative photomicrographies from SEM-EDS of fraction between 1.2 and 0.60 mm are presented in Figure 10. In the BSE image, the lighter phase is represented by ceramic fragments and feldspars, intermediate grey by quartz and the darker grey by cement paste. In the X-ray composed mapping, quartz is represented by the colour blue, cement paste by magenta and feldspars are orange.

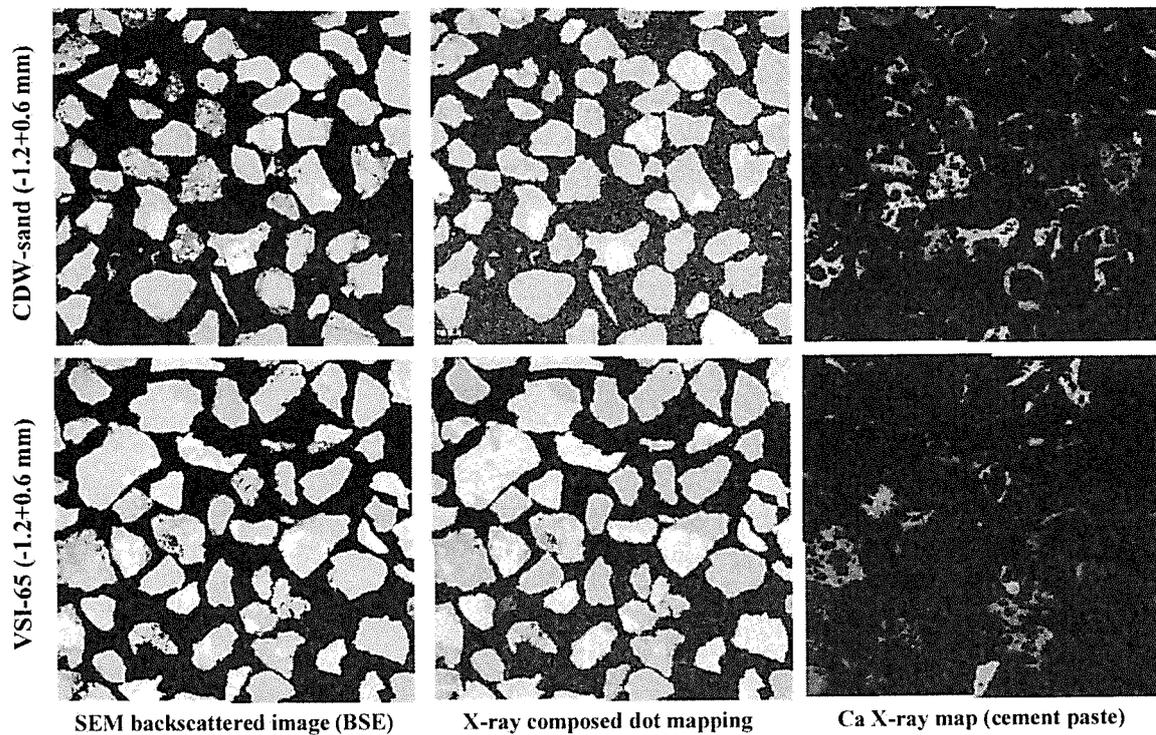


Figure 10 Images from SEM (a) backscattered images, (b) composition mapping, (c) cement paste mapping

In CDW-sand, cement paste occurs both by bonding small grains of quartz (sand) or adhered to particles surface. The sand produced from crushed C&D waste has high content of particles from the fragmentation of natural aggregates (almost free from binder); the decreases in cement paste attached to the aggregates surface is also remarkable.

The aggregates with small grains of quartz (sand) observed in the CDW-sand remain are present in VSI-sand, indicating that liberation/fragmentation is not properly achieved for this size fraction.

CONCLUSIONS

It is important to emphasize that the sand fraction originally present in crushed C&D waste represents around 50% of the total waste (Ulsen *et al.* Recycle 2009); this fraction is not preferably produced; it is generated as a result of the breakage of C&D materials during demolition, handling, transportation and production of coarse recycled aggregates. In addition, the focus on the production of recycled sand as a main product is not usual, but the results shown herein confirm that this approach might be interesting to diversify the recycled products and thus to expand the recycling market.

The grain size analysis demonstrates it is possible to produce sand from C&DW with similar grading of the original sand fraction present at the total waste. Besides, the rock-on-rock comminution by vertical shaft impact crusher (VSI) improved the morphology of recycled sand, when compared to the morphology of sand from C&D waste.

The content of cement paste is estimated by the sum of CaO grade plus LOI values, according to the literature. The CDW-sand presents a higher relative amount of cement paste in fractions above 0.15 mm as compared to the crushed sand, indicating that comminution concentrates the cement paste on fractions below 0.15 mm. Besides, the crushing step produces sand enriched with aluminium silicates, mainly feldspars from virgin aggregates. The results of the heavy liquid separation, water absorption and porosity clearly demonstrate the difference among the samples and the diminished porosity for VSI sand.

The comparison among the different crushing conditions indicates that the rotor speed did not have a crucial influence on the grading of the recycled sand or on the particles shape. On the other hand, the cement paste content and distribution is influenced by this parameter. Besides, the results of density distribution, water absorption and porosity showed that the rotor speed influences the porosity of particles.

In conclusion, the comminution by vertical shaft impact crusher allowed producing a VSI-sand with low porosity and water absorption. This change in sand recycling approach contributes to the upcycling of C&DW sand fraction.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support provided by the National Counsel of Technological and Scientific Development (CNPq) and by the Polytechnic Engineers Association (AEP). The technical support provided by Micromeritics, Urbem Tecnologia Ambiental and Metso Minerals were also fundamental for the development of this research, the authors recognize its significance.

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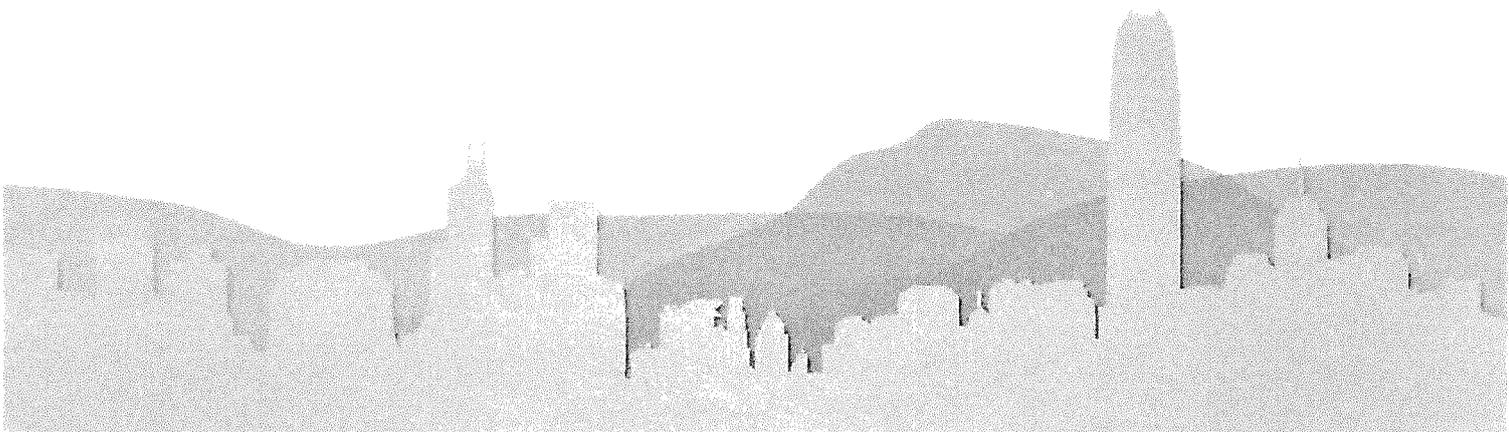
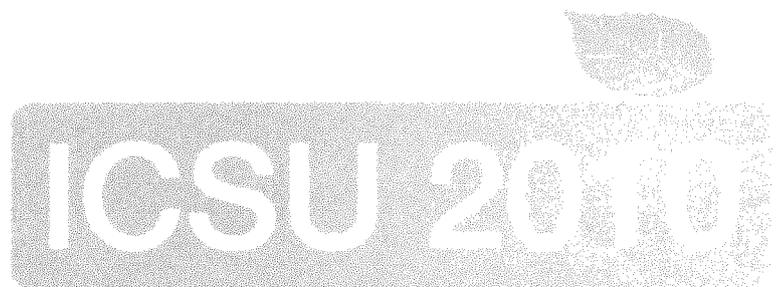
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Proceedings of the First International Conference on Sustainable Urbanization

15-17 December 2010
Hong Kong, China

Editor: J.G. Teng



PREFACE

Massive urbanization programmes are under way in many parts of the world, often in regions where the available land and resources are limited relative to the size of the population (e.g. the Chinese mainland). While urbanization is an inevitable corollary of economic development and industrialization, it nonetheless leads to many challenges. Such challenges include the provision of effective urban infrastructures (e.g. transport systems), adequate housing, sufficient energy and water supplies, a clean environment and a caring community support system. These challenges, phenomenal in their own right, are further amplified by the severe problems already facing the world, including climate changes and limited energy and water supplies. Against this background, the First International Conference on Sustainable Urbanization (ICSU 2010) was organised by the Faculty of Construction and Land Use (FCLU) of The Hong Kong Polytechnic University, to provide an international forum for the scientific/engineering community to examine these challenges, and to find effective solutions to ensure a sustainable process of urbanization as well as sustainable management of urbanized areas.

The proceedings of the Conference comprise two parts: (i) a printed volume that contains the full papers (or abstracts if full papers were not submitted) of 4 Keynote Lectures and 19 Invited Lectures as well as the abstracts of 244 papers arising from free submissions; (ii) a USB drive that contains all full papers (or abstracts if full papers were not submitted). It is hoped that this hybrid format would strike a good balance between ease of access and size of the volume. The papers had come from 27 countries around the world and cover a wide range of issues concerning urban infrastructure development, supply and efficient use of energy, and the achievement of a sustainable urban environment. Showcasing diversity and quality, these papers report the current state-of-the-art and point to future directions of research in this exciting area.

The success of the Conference told the story of dedication by and support from many individuals and organizations. On behalf of the Organizing Committee, I would like to thank all authors for their careful preparation of the manuscripts, and all Keynote and Invited Speakers for sharing their work, experience and insight at the Conference. All papers submitted to the Conference were reviewed by members of the International Scientific Committee and the Organising Committee as well as other experts around the world. The two Committees also generated widespread interest in and support for the Conference both within and outside Hong Kong. We are grateful to all of them for their important contributions to the Conference. Thanks are also due to our Conference Advisors for mobilizing local support for the Conference.

In addition to sharing the paper review task, members of the Organising Committee have also been most generous with their time in the organization work. As Chairman of the Organising Committee, I am indebted to all of them and particularly the Sub-Committee Chairs, the Mini-symposium Chairs and the three Co-secretaries who all toiled through a protracted process only to ensure the success of the Conference.

I would like to express my special thanks to two former Deans of the Faculty, Professor Mike Anson and Professor J.M. Ko, who have been active promoters of sustainable urbanization research and have provided advice and assistance during the organization of the Conference. In particular, Professor J.M. Ko played the pivotal role in securing financial sponsorships from the local industry for the Conference.

The Conference has received financial support from 11 organizations; their generosity is acknowledged with heartfelt gratitude. In particular, the Environment and Conservation Fund provided financial support for our overseas Keynote and Invited Speakers, K.C. Wong Education Foundation funded our Keynote and Invited Speakers from the Chinese mainland, while Road King Infrastructure Limited and Sun Hung Kai Properties were the two Diamond Sponsors of the Conference. I look forward to their continued support for future events of the Faculty.

We have had the pleasure of working with 18 organizations as non-financial sponsors of the Conference. They provided multifarious channels for publicising the Conference and for mobilizing international interest in it. I thank all of them for their support and hope that the rapport established through this collaboration will bear new fruits in future years.

Our thanks go to the Conference Secretariat, comprising Ms Carrie Chan, Ms Liz Lau and Ms Yo Yo Tsui, for their tireless effort throughout the organisation of the Conference. Thanks are also due to all colleagues in the FCLU office, led by Ms Carmen Lee, who have offered help in innumerable ways during the organisation of the Conference.

Professor Timothy Tong, President of PolyU opened the Conference on 15 December 2010 while the Honourable Ms Marjorie Yang, JP, Chairlady of the PolyU Council, was the dinner speaker on 16 December 2010. I am grateful to both of them and the wider community of the University for the support and encouragement we received in the course of organising this Conference.

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