Producción de hormigón reciclado. Reciclaje repetitivo de agregados gruesos de hormigón

Recycled concrete production. Multiple recycling of concrete coarse aggregates

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Fecha de recepción: 03/ 12/ 2004
Fecha de aceptación: 27/ 03/ 2006
PAG. 33 - 40

Resumen

Agregados reciclados, como aquellos empleados en la realización de camadas de base y sub-base de carreteras, y como los utilizados en substitución de agregados naturales en la producción de hormigón, pueden contribuir de modo importante en la reducción de consecuencias negativas en el ambiente, derivadas de la producción y depósito de residuos de construcción y demolición. En el ámbito de trabajo de investigación en curso, realizado en el Instituto Superior Técnico (IST) de Lisboa, se presentan en este artículo los resultados de un proyecto de análisis experimental. El principal objetivo fue demostrar la viabilidad técnica del reciclaje repetitivo de agregados gruesos obtenidos de la demolición de elementos existentes de hormigón para la fabricación de un nuevo hormigón sin utilizar agregados gruesos naturales. Los resultados, en términos de resistencia a compresión y slump, muestran que el hormigón producido después del reciclaje repetitivo de los agregados tiene aproximadamente las mismas características que el obtenido después del primer ciclo, lo que prueba que el proceso puede ser reproducido sin más limitaciones.

Palabras Clave: Agregados reciclados, hormigón, comportamiento mecánico, sustentabilidad

Abstract

Recycled aggregates, such as the ones used in making the sub-base and base layers of roads and the ones used as replacement of natural aggregates in concrete production, may give an important contribution towards decreasing the negative consequences that production and dumping of construction and demolition waste nowadays impose on the environment. Within the research work being carried on at Instituto Superior Técnico (IST) in Lisbon, the results of an experimental research project are presented in this article. Its main purpose was to demonstrate the technical sustainability of multiple recycling of coarse stone aggregates originally obtained from the demolition of existing concrete elements to make new concrete with no further consumption of any coarse natural aggregates. The results, in terms of compression strength and workability, show that concrete produced after multiple recycling of aggregates has approximately the same characteristics as the one obtained after only one cycle, thus proving that the process can be reproduced with no further limitations.

Keywords: Recycled Aggregates, concrete, mechanical behaviour, sustainability

1. Introducción

The production and dumping of construction and demolition waste (known as CDW) has been peaking in the last decades, especially in countries still undergoing a strong development surge, such as Portugal. According to a report prepared by the Symonds group (UK) (ETN, 1999) presented in 1999, the production of CDW in the European Union reaches approximately 180 million tons per year. Of this total, around 28% is recycled, the rest being directed to dumps. In Portugal, according to this report, less than 5% of the total quantity of CDW is recycled, a trend common to Spain, Greece and Ireland.

The situation portrayed above represents high costs both in environmental and energetic terms. Open-air dumps, frequently outside the legislation (Figure 1), are an aggression to environmental aesthetics, disrespect public and private rights, are responsible for a decrease in arable acreage and can potentially lead to air, underground water and soil pollution (even though CDW are included in the less hazardous waste class to the environment).

Indirectly, the fact that the CDW aggregates are not reused contributes to the continuation of the dilapidation of the natural resources in stone quarries, genuine sores in the rural landscape, or in river beds eventually leading to structural calamities as it happened recently in the North of Portugal, where a bridge (Figure 2) collapsed partly due to the unchecked extraction of sand killing 70 people. In Portugal, where the main sources of natural sand are riverbeds and sea coastal areas, this problem is bound to increase. In other countries, such as the Netherlands, Denmark and (the North of) Belgium, the scarcer materials are the coarse natural aggregates.

On the other hand, all the energy spent in cutting and crushing the original natural aggregates is thus wasted.

Figure 1. Open-air illegal dumping ground

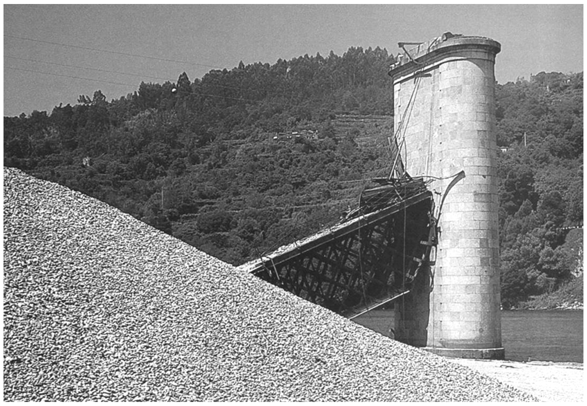

Figure 2. Entre-os-Rios Bridge after its collapse and sand extracted from the riverbed

One of the main objectives of CDW recycling is therefore profiting again from the portion of aggregates that they contain in the production of new construction materials, aiming at two environmentally minded goals: the reduction of the dumped waste volume and the decrease of the extraction of natural aggregates, a non-renewable resource. The research presented here is therefore integrated in general theme of Sustainable Construction.

2. Recycling: a wide domain with much research needed

At Instituto Superior Técnico (IST), the main engineering university in Lisbon, Portugal, a wide range of experimental projects has been under way in the field of construction and demolition waste recycling[1], with special emphasis on the production of structural concrete with coarse recycled aggregates obtained from demolished concrete elements. This work has already resulted in a Master Thesis in Construction, entitled “Analysis of the Performance of Concretes Made with Recycled Aggregates from Construction Waste” (Gonçalves, 2001), whose main experimental results are analyzed in the present article.

It must be referred that this research deals with nothing but a small fraction of the one needed within this vast domain. Without trying to be meticulous, it should be referred that concrete construction is not the only, or even the main, utilization given to recycled aggregates, nowadays more directed to the making of sub-bases and bases for roads and to landscaping of abandoned quarries and mines. The aggregates may be obtained from the waste of demolishing concrete elements (the case presented here), ceramic masonry elements (bricks and tiles) without any mortar attached (a Masters thesis dealing with the use of this debris in concrete production was also concluded), and a mix of ceramics with cement-based mortar or non-pre-selected demolition waste. Of these several options results the type of aggregate recycled: stone (the case under study), ceramic, a mixture of both or a mix of cement-based and ceramic elements with debris of several origins (wood, plastics, glass, etc.).

The recycled aggregates themselves may correspond only to the coarse fraction (the case under study), the fine fraction or both. Finally, the replacement

[1] Studies have been finished or are under way on the following subjects: mechanical performance and durability of concrete made with recycled concrete coarse aggregates; mechanical performance and capillarity of concrete made with recycled ceramic (red brick) coarse aggregates; mechanical performance and durability of concrete made with recycled concrete fine aggregates; implementation of a fixed recycling plant for RCD in the Lisbon area; preparation of technical specifications for the use of recycled aggregates from RCD on mortars and concretes.

of natural aggregates by their counterpart in terms of recycled aggregates can be total (the case under analysis) or partial.

Furthermore, the concrete (or mortar) made with recycled aggregates needs to have all his properties analyzed (and not only compression strength as in the present analysis): tension strength, abrasion resistance, modulus of elasticity, shrinkage, creep, gas, oxygen and water absorption (by immersion and by capillarity), carbon dioxide and chloride penetration rate, electric resistivity, among others.

In the last years, several European Union countries have developed research works regarding the use of recycled concrete aggregates in concrete structural elements. In the UK, a partner research project was led by BRE (Building Research Establishment) concerning the recycling of rejected precast elements within precast works. Initial test results showed that there was little effect replacing 20% of the coarse aggregate and 10% of the fine aggregate with recycled aggregates produced from reclaimed products (Collins, 1998).

In Belgium, a company specialized in the manufacture of precast structural elements (Van Acker, 1998) has also carried out research works to establish the influence of different proportioning of recycled waste concrete on the properties of the fresh and hardened concrete.

In Germany, tests were carried out to evaluate the effect of using recycled aggregates made of original concretes of different strengths on the properties of new concrete. The tests indicated that the strength of the original concrete has no significant effect on the strength of the recycled aggregates or the properties of fresh and hardened concrete (Dillman, 1998).

In Denmark, the Environment Ministry has financed several research projects and pilot-plants. In one of these, the co-called Recycled House has been built with aggregates obtained from the demolition of concretes overpasses. Technical specifications for the use of natural aggregates have been added with a chapter concerning recycled aggregates, in which two strength categories were considered for recycled aggregates concretes and their characteristics related with the ones of the original natural aggregates concretes.

The knowledge of the technical performance of concretes produced with recycled concrete aggregates is yet far from having been achieved. The thermal, acoustic and hygrometric behavior of concretes and mortars made with this type of aggregates requires huge resources in terms of research, and the same can be said about their durability (water and oxygen permeation rates, alkali-silica and sulfate reactivity, carbon dioxide and chloride penetration rates, additional protection materials, etc.), a subject being presently researched at IST, within a PhD Thesis preparation.

Other research topics involving CDW include the preparation of technical specifications and test methods specific for these materials (both concretes and mortars), the analysis of demolition, crushing and separation techniques (in order to minimize costs, works duration, environmental impact and discomfort to the neighborhood and to maximize safety levels and recycling ratios), the technical and economic feasibility of resorting to recycled aggregates (impact on the natural aggregates extraction industry, taxes repercussions, possible subsidies, costs / benefits analysis, etc.), the definition of sustainable dumping politics (both at a municipal and a national level, dealing with such matters as type and localization of adequate CDW dumps, dumping fees and recycled aggregates costs, subsiding this industry, etc.), the analysis of the environmental impact of (not) recycling (air, water and soil contamination), the question of the regulations and laws (fundamental to implement viable and sustainable politics for CDW) and their fulfillment and supervision. A more detailed list of research subjects is presented in (Brito and Santos, 2002). The research being made in Brazil (Levy, 2001) (Leite, 2001) (Pinto, 2001), mostly at the University of São Paulo, is a good example of a systematic approach to this problem.

An experimental research project in which the compression strength and the workability of concretes produced with a total replacement of the coarse aggregates by recycled stone aggregates obtained from crushing concrete elements is reported in this article. The innovation of this research arises from the fact that the aggregates are recycled repeatedly and not just once.

3. Multiple aggregates recycling

The experimental research referred here aimed at demonstrating the short-term technical feasibility of repetitive recycling of coarse aggregates obtained from structural concrete elements in the production of new elements of the same material.

In order to do achieve this goal, the conditions under which in practice this type of procedure can be achieved were tentatively reproduced, i.e. where a certain amount of concrete debris whose origin more or less unknown is collected. In this case, only the compression strength was known beforehand leading the concrete to be labeled a C32/40, according to Eurocode 2 (i.e. the 95% of the concrete compressive strength results, as measured in 150 mm cubes aged 28 days, falls within the interval from 40 to 45 MPa).

This material was crushed and, in the production of test cubes, the whole amount of the coarse natural aggregates was replaced by the coarse aggregates obtained from the crushing (100% replacement of the coarse aggregates). This process was repeated in three full cycles.

Figure 3. Test cubes before being crushed

4. Sequence of testing

One of the preconceived ideas associated with concretes produced with recycled aggregates (namely from demolished concrete) is their supposedly weak mechanical strength. In order to contest this preconception, a relatively strong original concrete (class C32/40) was deliberately chosen as well as a mixing composition for new concrete that gave some guarantees about its future mechanical capacity. However, it must be stated at this stage that establishing comparisons between concrete produced with natural aggregates and concrete made with recycled aggregates was not an objective of this particular experimental project[2].

The original concrete came from a set of seventy-one standard test 150 mm cubes obtained from LNEC, the Portuguese National Laboratory of Civil Engineering in Lisbon (Figure 3), where they had been tested. Its compressive strength was established (in all specimens between 40 and 45 MPa), but not its mixing composition, the origin of the components or its workability, since they were collected from more than one construction site.

These cubes were taken to an urban waste recycling plant's crushing unit (Figure 4) where they were jaw crushed, and all the products from this crushing were collected and taken to the laboratory. The percentage of this material capable of being recycled (taking into account that only the coarse aggregates - the ones retained by the 2.38 mm sieve - were appropriate and that their maximum diameter was limited to 24.4 mm) was determined.

Figure 4. Recycling plant where the concrete cubes were crushed

Samples of the recycled portion were collected in order to proceed with its grading. The respective grading diagram was plotted (Figure 5) as well as the one for the fine aggregates (natural sand).

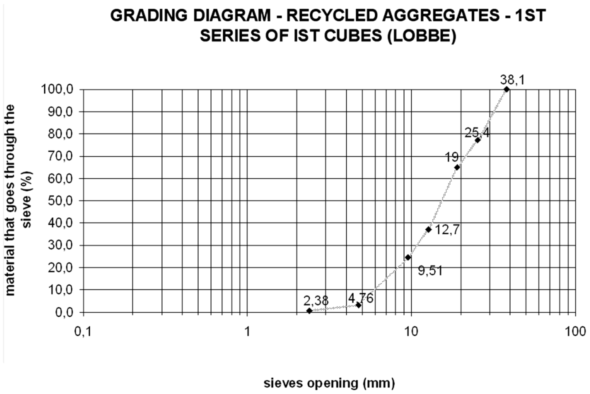

Figure 5. Sieve analysis of the coarse recycled aggregates from recycling cycle Nº 1

[2] Such comparisons have been made in many publications such as (de Brito and Gonçalves 2001), where it was shown that, in order to maintain the concrete cement and admixtures contents and the workability at the same time, the water / cement ratio has to be increased when natural aggregates are replaced by recycled ones, thus leading to reductions in strength, modulus of elasticity and increases in shrinkage and creep.

One of the most important problems in recycled aggregates is their water absorption, substantially higher than the one of natural aggregates. Consequently, this characteristic was determined according to the standard sequence of Portuguese Norm NP 581.

The concrete mixing composition was designed using the Faury's reference curves method. This composition, besides the objective referred above of helping in achieving a strength grade of the new concrete similar to the one of the original one, aimed at an acceptable workability level (a slump between 20 and 40 mm in the Abrams cone) without resorting to a too high water cement ratio (w/c) (as a compensation for the high water absorption). The long-term objective was to preserve the durability of the new concrete in an indirect way, since the negative influence that a high w/c ratio has on this characteristic and on its mechanical performance (Santos et al., 2002) is well known.

In order to do that, the apparent water / cement ratio was then maintained at a level (0.45) thought to be similar to the one of the original concrete, at the cost of adding a plasticizers agent (1.6 l/m^3) and increasing the cement content to a rather high value (450 kg/m^3), when in the original concrete very probably no plasticizers were used and the cement content was almost certainly at least 50 kg/m^3 lower than the one used in the concrete with recycled aggregates.

The mixing composition (per cubic meter of concrete) was as follows:

- 450 kg of cement;
- 730 kg of natural sand;
- 1040 kg of recycled coarse aggregates (not pre-wetted);
- 202.5 l of water (w/c = 0.45);
- 2.4 l of a plasticizer agent.

The workability (slump in the Abrams cone) of the mixes, three for each recycling cycle, was determined (in order to keep it fairly constant) and thirty 150 mm cubes were produced and wet-cured until they were 28 days old. The cubes were subjected to the ultimate compression stress test in accordance with the ASTM C39 standard. The following values were determined: mean value, standard deviation, variation coefficient and characteristic value, corresponding to the 5% fractile in a Gauss normal distribution, thus ending recycling cycle Nº 1.

Cycle Nº 2 started with the crushing of the cubes in the same recycling plant as in the previous cycle, and the general procedures described for cycle No. 1 were repeated. It must be stressed that exactly the same concrete mixing composition was used, notwithstanding the increase registered in the water absorption of the coarse aggregates recycled for the second time (from 6.3% to 7.6%). Since the mixer capacity forced the use of three mixes per cycle (30 15 cm cubic specimens were to be produced in each cycle), some variations to the basic composition were tried, even though the results were not always perfectly conclusive.

A third recycling cycle was performed, identical in general to the previous ones (including the concrete composition even though the coarse aggregates water absorption further increased to 8.5%) except for the fact that the cubes from the previous cycle were crushed in a smaller jaw crusher (Figure 6) from the Mines Department of IST, for time saving purposes, to obtain the new recycled aggregates.

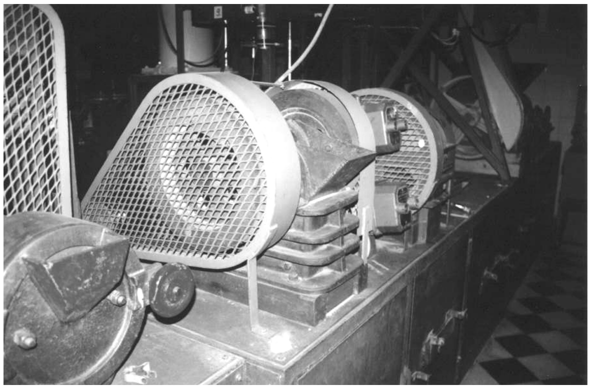

Figure 6. Small crushing unit used in cycle Nº 3

5. Analysis of the results obtained

The main results of the three recycling cycles are the mixes workability (as translated by the respective slump in the Abrams cone, Δ), the concrete compressive strength (quantified by the characteristic value of the ultimate compressive stress, f_{ck}, and by the strength grade attributed, i.e. the concrete class according to Eurocode 2) and the water absorption of the coarse recycled aggregates (given as a percentage by c_{wa}). The presentation of the values obtained is made on Table 1 and its explanation and discussion follow.

Table 1. Summary of the results obtained in the three recycling cycles

CYCLE No.	SLUMP (Cone of Abrams)	ULTIMATE COMPRESSIVE STRESS	CONCRETE CLASS (EC2)	RECYCLED COARSE AGGREGATES WATER ABSORPTION
1	2.8 cm	42 MPa	C32/40	6.3%
2	5.3 cm	40 MPa	C32/40	7.6%
3	3.3 cm	46 MPa	C35/45	8.5%

The average value of Δ in the three mixes was 2.8, 5.3 and 3.3 cm, for cycles No. 1, 2 and 3 respectively. Since the concrete mixing composition and namely the apparent water / cement ratio were kept constant (w/c = 0.45) in the three cycles, and keeping in mind, as will be shown further on, that the water absorption of the recycled aggregates kept increasing, it was expected that the workability of the mixes and, consequently, the value of Δ were to decrease from one cycle to the next.

The value obtained in cycle Nº 2 clearly fell slightly outside that tendency. Since the effective water / cement ratio (meaning the water that is not absorbed by the aggregates and is thus used to hydrate the cement and to contribute to the workability of the fresh concrete) was not measured, it is not possible to conclude positively that it increased in this cycle, as compared with the others. However, that is most probable and is also a possible explanation for the slight decrease in the ultimate compressive strength in the second cycle.

The values of f_{ck} obtained sequentially in the three cycles were 42, 40 and 46 MPa, corresponding to the following concrete strength grades: C32/40 (identical to the original concrete made with natural aggregates only), C32/40 and C35/45. Thus, some fluctuation, even though not very significant, was registered around the value of 42 MPa, which means that the concrete strength tended to be rather stable along the recycling cycles. It is thought that this trade was only slightly altered because of the weather conditions, to which the characteristics of the concretes produced with recycled aggregates seem to be particularly sensitive.

This sensitivity would probably have been eliminated, or at least strongly toned down, if effective water / cement ratio had been kept constant, i.e. taking explicitly into account the growing absorption of the recycled aggregates. There is one other factor that may have affected the results obtained in cycle Nº 3: a change in the grading diagram (Figure 7), more evenly spread out, as a result of the different crushing unit used (Figures 4 and 6).

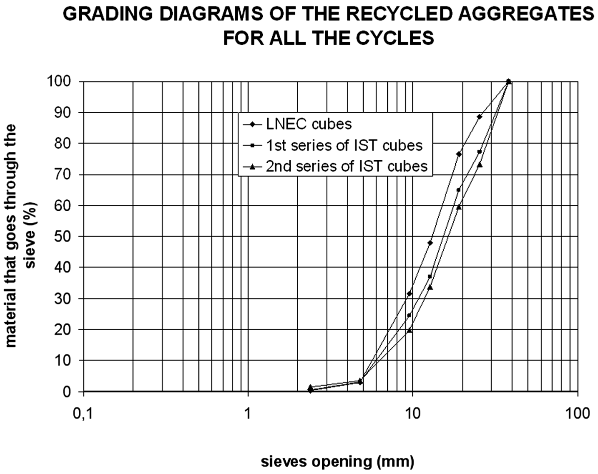

Figure 7. Sieve analysis of the recycled aggregates used in the recycling cycles

A very interesting aspect worth registering and which contradicts somehow some bibliographic references on this subject that report a significant variability of the strengths obtained in concretes made with recycled aggregates, was the fact that the variation coefficients obtained in the compressive strength tests in the three cycles were particularly low (even though corresponding to two or more often three different mixes): 3.4%, 2.6% and 1.8%. Notwithstanding the fact that these mixes were made under laboratory conditions, these results clearly demonstrate that the concretes produced with recycled aggregates can be as reliable, at least in mechanical terms, as the ones produced solely with natural aggregates.

In terms of water absorption of the coarse aggregates, the values of c_{wa} obtained along the three cycles were as follows: 6.3%, 7.6% and 8.5%. It becomes therefore clear that the mortar portion that comes attached to the stone aggregates in each crushing operation forces the latter's absorption to keep increasing. It is not possible, with the number of cycles performed, to conclude with certainty whether this growing trade will go on indefinitely or the absorption will tend asymptotically to a fixed even if high value. However, it is clear that this is the main problem concerning the use of recycled aggregates, since the natural aggregates absorption rarely goes over 1%, depending on the nature of the stone.

By governing the workability of fresh concrete, the water absorption of the aggregates leads to one of the two following consequences, if one wants to keep the fluidity of the mix: by maintaining the remaining components, the quantity of water will have to be increased, with all the negative consequences that the increase of the water / cement ratio has on the long-term strength (in terms of compression, tension, modulus of elasticity, abrasion resistance, etc.) and especially on the durability (in terms of compacity, with direct consequences in such phenomena as carbonation, chloride ingress and others); in order to maintain the water / cement ratio, either the dosage of cement will have to be increased, plasticizers or superplasticizers will have to be resorted to, or both measures will have to be taken (as was done in the present experimental project, which explains the high cement dosage used - 450 kg/m^3 - and the use of a plasticizer).

It was thought that this second strategy is the most adequate strictly from a structural point of view (even though not in terms of the environment), even though it implicates extra costs in the concrete production (this question has also been addressed from an economic point of view in (Brito and Gonçalves, 2001), and it was proved that mild environmental taxes on quarry procedures and dumping grounds are enough to even things out). It must be stressed that this need, valid in the change from natural stone aggregates only to its replacement even if partial by recycled concrete aggregates, was apparently not felt in multiple recycling, judging from the results. Furthermore, resorting to better quality cements and a superplasticizer could decrease the additional quantities of cement and plasticizer.

6. Conclusions

The process of multiple recycling of stone coarse aggregates recycled from concrete elements to produce new concrete has every condition to be self-sustainable with no time limits. In terms of strength, it is possible to maintain it at a more or less steady level without changing the mixing composition. The workability of the fresh concrete is also capable of staying stable without resorting to an increase of the apparent water / cement ratio. This last fact gives good indications in terms of the expectable durability, even though specific research is needed to demonstrate it.

Finally, the economic sustainability has been demonstrated in practice in several Northern and Central European countries (Denmark, Flanders in Belgium, the Netherlands) and in theory in Portugal (Brito and Gonçalves, 2001), notwithstanding the need, in cycle No. 1 (introduction for the first time of a fraction of recycled aggregates instead of crushed natural stone), of resorting to greater dosages of cement and plasticizers. However, this is only possible within an environmentally minded state or municipal policy that penalizes dumping and non-renewable recyclable resources dilapidation and promotes recycling plants and products / technologies with recycled materials.

7. Acknowledgements

The experimental work presented in this article was performed in the Construction Laboratory of the Civil Engineering and Architecture Department of Instituto Superior Técnico (IST), Lisbon, as part of a Master thesis within the Master course on Construction of the same department. Financial backing from the research center ICIST at IST is also acknowledged.

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