Pergamon

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Cement and Concrete Research 34 (2004) 1975–1980

CEMENT AND CONCRETE RESEARCH

# Durability of recycled aggregates concrete: a safe way to sustainable development

Salomon M. Levy[a,b], Paulo Helene[b,c,d,*]

[a]Centro Universitário Nove de Julho (UNINOVE), São Paulo, Brazil
[b]Brazilian Concrete Institute (IBRACON), São Paulo, Brazil
[c]Polytechnic School, University of São Paulo, São Paulo, Brazil
[d]Rehabilitar Network CYTED XV.F, Madrid, Spain

Received 18 March 2003; accepted 10 February 2004

**Abstract**

Fine and coarse recycled aggregates recovered from demolished masonry and concrete structures were utilized in the manufacture of new concrete mixtures. Three properties of these new concretes were analyzed: water absorption, total pores volume, and carbonation. The recycled concrete families were created by replacing parts of the natural aggregates forming families of concrete with 0%, 20%, 50%, and 100% of aggregates from recycled sources. The usual comparison between mixtures by comparison between behaviors of concrete families. This research shows that the mix design nomogram (MDN) is a new and useful tool that allows the researchers to compare properties and behaviors of different concretes. The results show that the family concrete with the highest pore volume and with the same compressive strength of 20, 30, and 40 MPa (2900, 4350, and 5800 psi) did not always correspond to the concrete family with the highest degree of carbonation. This experiment also showed that some compositional characteristics of concrete could have more influence on the durability that the traditional physical aspects.


*Keywords:* Absorption; Carbonation; Corrosion; Durability; Waste management

## 1. Introduction

Every aggressive agent present in the environment surrounding a concrete structure can percolate, diffuse, and penetrate across the pores of the concrete according to transport mechanism laws. Water absorption by immersion and total pore volume are considered better indicators in evaluating the potential durability of concrete than capillary absorption, which only occurs under special circumstances in which the concrete is not saturated and is in the presence of water. Furthermore, indirect ways of evaluating concrete durability, such as porosity studies, can be insufficient for measuring the effectiveness of behavior of the concrete in the presence of aggressive external agents. This research could demonstrate that knowing and weighing the influence of the type of concrete, and its composition in recycled aggregate is more important than its physical characteristics in the performance analysis of recycled concretes.

Wirquin et al. [1], in 2000, reported that a study of water absorption in recycled aggregate concretes showed that the processes of water absorption in recycled aggregate and in natural aggregate concretes are similar and obey the same laws. In addition, Mehta and Monteiro [2] reported that the water, as a primary agent, is able to create and degrade natural and artificial materials, as concrete. It is also a central factor behind for most of the problems regarding concrete durability, as water works as a transport vehicle for aggressive ions and as a cause of chemical processes causing physical and mechanical degradation of concrete structures.

Water, ions, and gas penetrating the concrete also can change the concrete degradation kinetics during the structure service life. This investigation shows that it is possible to evaluate the influence of recycled aggregates to the depth of carbonation of concrete and that $CO_2$ gas penetration depends on the cement's composition, porosity, and aggregate mineral composition (i.e., chemicals aspects).

* Corresponding author. Polytechnic School, University of São Paulo, Av. Prof. Almeida Prado, trav. 2, 83, São Paulo 05508-900, Brazil. Tel.: +55-11-3091-5442; fax: +55-11-3091-5544.
*E-mail address:* paulo.helene@poli.usp.br (P. Helene).

0008-8846/$ – see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconres.2004.02.009

The use of mix design nomogram (MDN) introduced by Helene and Monteiro [3] allows the researchers to make a correct and relevant comparison between the different concrete families, adopting the same ascending reference compressive concrete strength like 20, 30, and 40 MPa (2900, 4350, and 5800 psi), instead of the usual poor comparison between individual mixture results.

## 2. Materials and methods

Blended Portland cement, comprised of 35% blast furnace slag, with a Blaine fineness of 385 $m^2$/kg, density of 2990 kg/$m^3$, with an average compressive strength at 28 days of 39 MPa (5655 psi) for W/C = 0,48, was used in all concrete mixtures. It is once the most frequent cement used in ordinary concrete structures in Brazil.

Fine natural aggregates, washed quartz river sand, presenting 2650 kg/$m^3$ density, with a fineness modulus (FM) of 2.6, and water absorption in saturated dry surface condition (SDS) of 1.8%, and coarse natural aggregates-type granite crushed as rock gravel, presenting 2700 kg/$m^3$ density, $D_{max}$ = 25 mm, with an FM of 7.0 and water absorption in SDS of 0.8% were used, once both are usual and safety aggregates in the São Paulo city region.

The fine and coarse recycled concrete aggregates (FRCA and CRCA) that were used had been obtained (crushed) from a homogeneous concrete structure 6 months old presenting 25 MPa (3626 psi) average compressive strength for an average W/C = 0.66, 2320 kg/$m^3$ density, $D_{max}$ = 25 mm, and FM = 6.6 for coarse aggregate, and $D_{max}$ = 2.4 mm and FM = 2.5 for fine aggregates, and its composition is cement paste made with the same blended cement, same granite as coarse aggregate, and same natural quartz river sand as fine aggregate. The FRCA and CRCA present 10.3% and 5.6% water absorption in SDS condition, respectively.

The fine and coarse recycled masonry aggregates (FRMA and CRMA) that were used had been obtained (crushed) from 1-year-old and homogenous clay brick walls covered with mortar made with cement, calcium hydroxide, and natural quartz river sand according to ASTM C 270 Type N [4]. In average, the fine and coarse aggregates present 76% clay and 24% mortar, 1890 kg/$m^3$ average density, $D_{max}$ = 25 mm, and FM = 6.5 for coarse aggregate and $D_{max}$ = 2.4 mm and FM = 2.5 for fine aggregates. FRMA and CRMA present 13.0% and 7.9% water absorption in SDS condition, respectively.

To obtain the recycled aggregates, the old concrete and masonry were passed through a jaw crusher and the resulting product was later subjected to a sieving operation. The fractions corresponding to fine and coarse aggregates were used to produce 12 concrete families, always in laboratory SDS condition. The results were compared with those given for a 13th concrete family, produced exclusively with natural aggregates and called reference concrete family.

### 2.1. Concrete mix proportion

Three dry aggregate/cement ratio by mass were used for each concrete family: 3/1, 4.5/1, and 6/1, all of which had the same fresh workability by slump test [70 ± 10 mm (3 in)], replacing natural aggregates by 0, 20, 50, and 100 mass% of recycled concrete or masonry aggregates. There are 13 concrete families, and 39 different concrete mix proportions were made.

The main tests were performed beginning at 28 days. All specimens were stored in a standard humid chamber, during their first 14 days; after which, they were kept exposed in a laboratory ambient (55–65% relative humidity and 20–26 °C).

### 2.2. Properties measured

The following were measured: compressive strength by ASTM C 39 [5], water absorption and total pores volume by ASTM C 642 [6], and accelerated carbonation test by RILEM CPC 18 method [7]. In addition, cement content, water content, water cement ratio by mass, entrapped air, slump test, and fresh concrete density were measured by conventional lab methods.

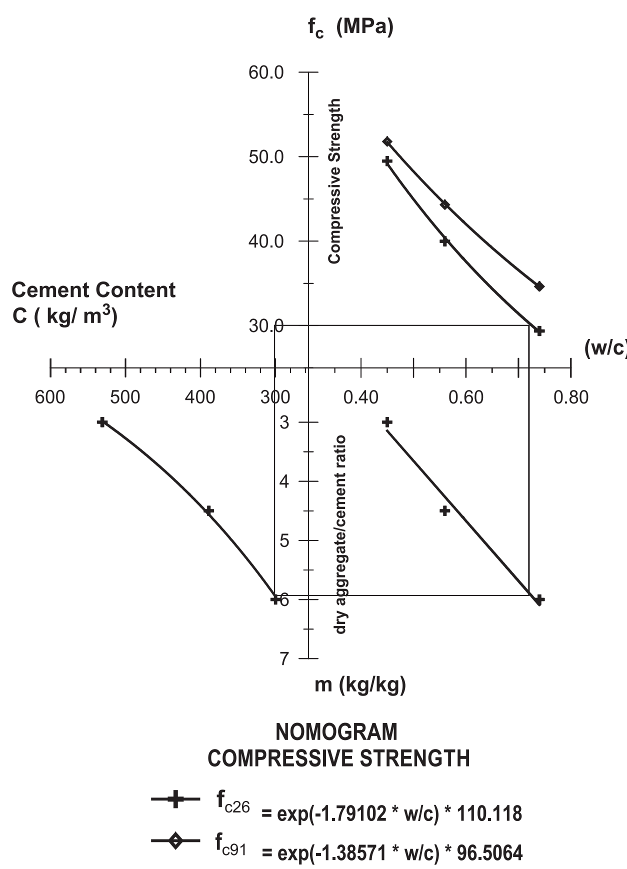


Fig. 1. Strength MDN for concrete family 50–50% FRMA.

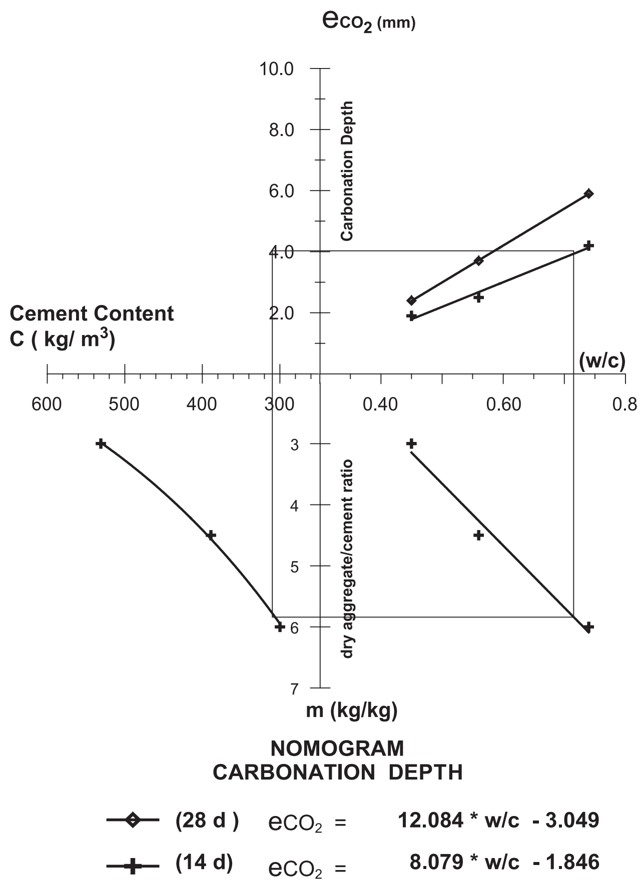


Fig. 2. Carbonation MDN for concrete family 50–50% FRMA.

## 3. Constructing the safety data for discussion

The first step is constructing an MDN for each 1 of the 13 concrete families; one for the natural aggregate concrete called reference concrete family, six for recycled concrete (three for FRCA and three for CRCA), and six for recycled masonry (three for FRMA and three for CRMA) (Fig. 1).

The second step is, using the corresponding MDN, obtaining the W/C ratio for each concrete family to get the desired compressive concrete strength of 20, 30, and 40 MPa (2900, 4350, and 5800 psi) at 28 days.

The third step is constructing the corresponding behavior for the durability properties by W/C ratio for each concrete family (Fig. 2).

The fourth step is obtaining the W/C ratio for compressive concrete strength desired (Step 2) to obtain the corresponding durability properties (carbonation, water absorption, and pore volume).

How each concrete durability property, with the type and amount of natural aggregate replaced by recycled aggregates to get the desired compressive concrete strength of 20, 30, and 40 MPa (2900, 4350, and 5800 psi) at 28 days, will be discussed next.

## 4. Discussion

Concrete water absorption increases when the amount of natural aggregates is being replaced by recycled aggregates (Fig. 3). This behavior is to be expected because the fine

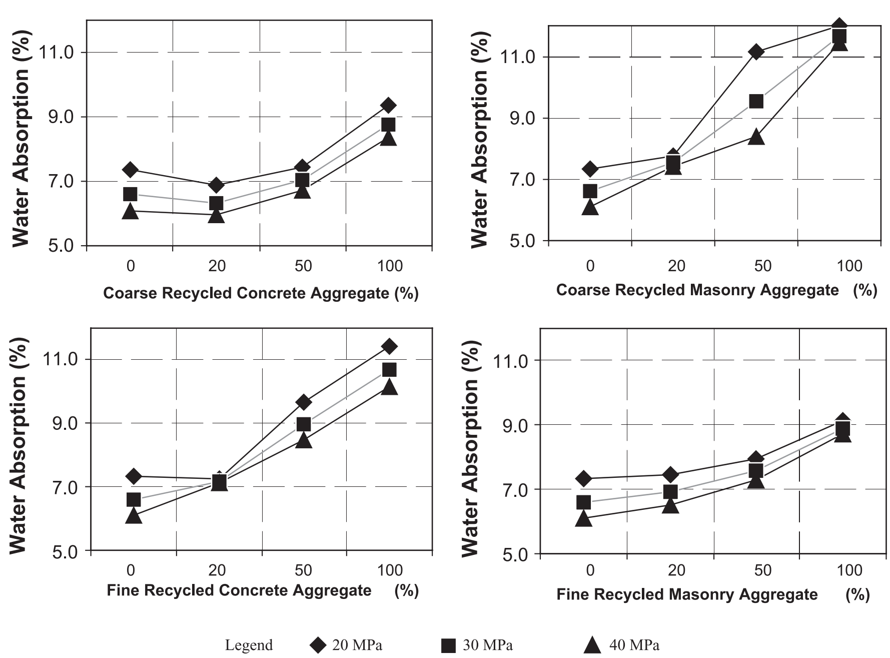


Fig. 3. Evolution of water absorption, with the amount of natural aggregate being replaced by FRCA, CRCA, FRMA, and CRMA to achieve 20, 30, and 40 MPa at 28 days.

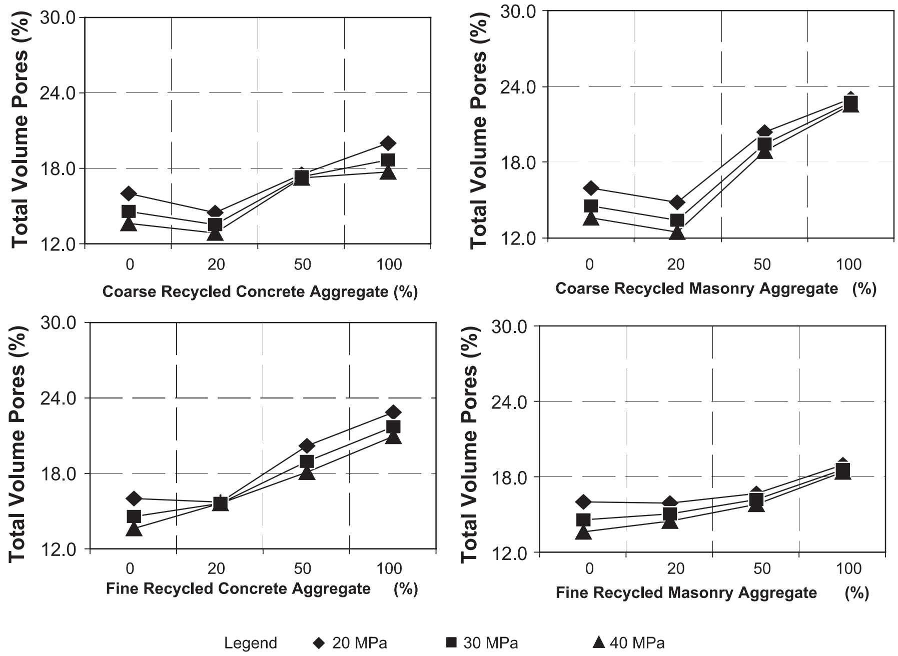


Fig. 4. Evolution of total pore volume, with the amount of natural aggregate being replaced by FRCA, CRCA, FRMA, and CRMA to achieve 20, 30, and 40 MPa at 28 days.

and coarse recycled aggregates obtained from masonry and concrete used in this research present 6–10 times more water absorption than natural aggregates.

The aforementioned expected behavior was not observed in the CRCA family when the replacement was 20%. The CRCA family presents lower water absorption than the reference concrete family. Similar exceptional behavior can be found in the total pore volume when the CRCA and CRMA families, both at 20% replacement, present lower total pores volume than the reference concrete family (Fig 4). This behavior for the CRCA family can be explained by considering the changes in the grading of aggregate composition (compacting factors). For the CRMA family, it is possible to consider the changes in aggregates grade and also justify using 20% as the most ideal pozzolanic proportions, in this case, of calcined clay

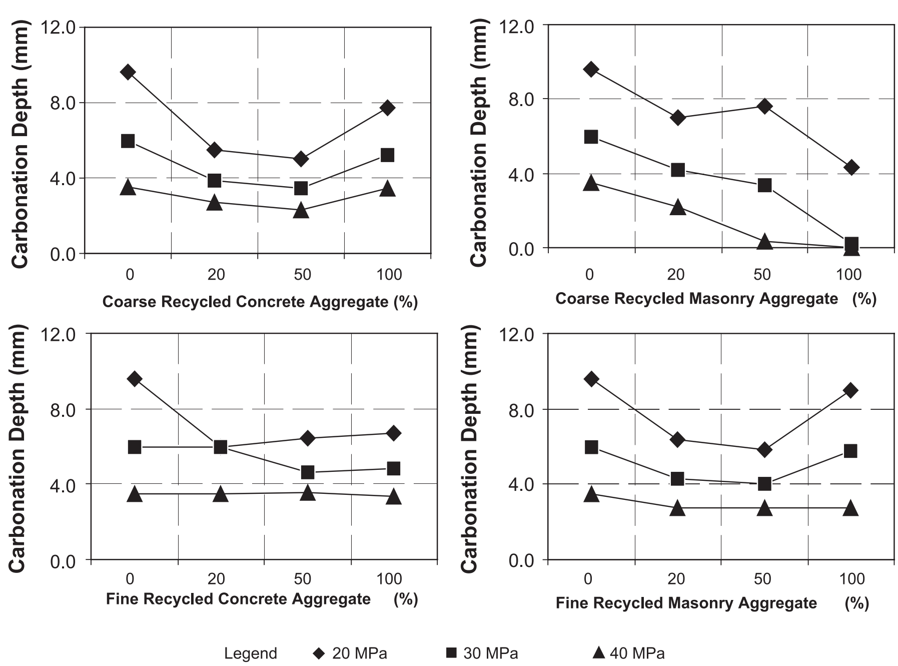


Fig. 5. Evolution of carbonation depth, with the amount of natural aggregate being replaced by FRCA, CRCA, FRMA, and CRMA to achieve 20, 30, and 40 MPa at 28 days.

Table 1
Cement content and carbonation depth for all concrete families

| Aggregates | Percentage of replacement | Cement content ($kg/m^3$) | | | Carbonation depth, $e_{CO_2}$ (mm) | | |
|---|---|---|---|---|---|---|---|
| | | $f_{c28}=20$ MPa | $f_{c28}=30$ MPa | $f_{c28}=40$ MPa | $f_{c28}=20$ MPa | $f_{c28}=30$ MPa | $f_{c28}=40$ MPa |
| Natural | 0 | 179 | 291 | 397 | 9.6 | 6.0 | 3.5 |
| CRCA | 20 | 269 | 341 | 407 | 5.5 | 3.9 | 2.7 |
| | 50 | 231 | 329 | 422 | 5.0 | 3.4 | 2.3 |
| | 100 | 190 | 293 | 392 | 7.7 | 5.2 | 3.4 |
| CRMA | 20 | 200 | 333 | 476 | 7.0 | 4.2 | 2.2 |
| | 50 | 279 | 417 | 569 | 7.6 | 3.4 | 0.4 |
| | 100 | 326 | 522 | 852 | 4.3 | 0.2 | 0.0 |
| FRCA | 20 | 239 | 325 | 404 | 6.0 | 4.6 | 3.6 |
| | 50 | 216 | 330 | 445 | 6.5 | 4.6 | 3.3 |
| | 100 | 266 | 366 | 461 | 6.7 | 4.9 | 3.6 |
| FRMA | 20 | 220 | 329 | 434 | 6.4 | 4.3 | 2.8 |
| | 50 | 191 | 300 | 407 | 5.8 | 4.0 | 2.7 |
| | 100 | 217 | 332 | 455 | 9.0 | 5.8 | 3.5 |

1 MPa = 145 psi.

(masonry) to react with calcium hydroxide from cement paste hydration [8]. In fact, it is hard to find the exact reason, and more studies are recommended for better understanding.

In general, the carbonation depth decreases when the amount of recycled aggregates increases, presenting a better behavior when this replacement was 20% or 50%, mainly for the recycled coarse and fine masonry aggregate.

When using masonry or concrete recycled aggregates, also with 100% replacement, the carbonation depth is still lower when compared with reference concrete made by natural aggregates (Fig. 5). The explanation of this can have support in the highest cement content of recycled concretes to achieve the same compressive concrete strength of natural aggregates concrete. Recycled concretes need more cement content to achieve the same strength compared with reference concrete, as shown in Tables 1 and 2. This higher alkaline reserve acts by protecting concrete surface against carbonation mechanisms. In addition to this, not only for recycled aggregates from old concrete but also for recycled aggregates from old masonry, the recycled aggregates are constituted partly by old mortar with cement and calcium hydroxide particles, which can increase the alkaline reserve of these recycled concretes.

The positive effect of the alkaline reserve in relation with carbonation can also be beneficial in increasing the service life [9] of concrete structures, because they reach more years without depassivation of reinforcement, which means increase in the initiation period [10].

## 5. Conclusions

Under the conditions of this research, the following can be concluded:

- Concrete made with recycled aggregates (20%, 50%, and 100% replacement) from old masonry or from old concrete can have the same fresh workability and can achieve the same compressive strength of concrete made by natural aggregates in the range of 20–40 MPa at 28 days.

Table 2
Water absorption and pores volume for all concrete families

| Aggregates | Percentage of replacement | Water absorption (%) | | | Pores volume (%) | | |
|---|---|---|---|---|---|---|---|
| | | $f_{c28}=20$ MPa | $f_{c28}=30$ MPa | $f_{c28}=40$ MPa | $f_{c28}=20$ MPa | $f_{c28}=30$ MPa | $f_{c28}=40$ MPa |
| Natural | 0 | 7.3 | 6.6 | 6.1 | 16.0 | 14.6 | 13.6 |
| CRCA | 20 | 6.9 | 6.3 | 5.9 | 14.5 | 13.5 | 12.9 |
| | 50 | 7.5 | 7.0 | 6.7 | 17.5 | 17.3 | 17.2 |
| | 100 | 7.3 | 8.0 | 8.4 | 15.3 | 16.8 | 17.8 |
| CRMA | 20 | 7.8 | 7.6 | 7.4 | 14.9 | 13.5 | 12.5 |
| | 50 | 11.2 | 9.5 | 8.4 | 20.4 | 19.5 | 18.9 |
| | 100 | 12.0 | 11.7 | 11.5 | 3.1 | 22.8 | 22.5 |
| FRCA | 20 | 7.3 | 7.2 | 7.1 | 15.8 | 15.7 | 15.6 |
| | 50 | 9.7 | 9.0 | 8.5 | 20.2 | 19.0 | 18.1 |
| | 100 | 11.4 | 10.7 | 10.1 | 22.9 | 21.7 | 20.9 |
| FRMA | 20 | 7.5 | 6.9 | 6.5 | 15.9 | 15.1 | 14.4 |
| | 50 | 8.0 | 7.6 | 7.3 | 16.7 | 16.2 | 15.8 |
| | 100 | 8.2 | 8.9 | 9.4 | 19.0 | 18.6 | 18.3 |

1 MPa = 145 psi.

- Minimum water absorption and total pore volume for the recycled aggregates concrete were observed at 20% replacement when using CRCA and CRMA. These can be explained by grade aggregate compacting factors and the ideal pozzolanic proportions. For all other conditions performed in this investigation, when water absorption and total pore volume are increased, the replacement of recycled aggregate also increases.
- In the recycled aggregates concrete performed in this study, the carbonation depth decreased when the replacement was 20% or 50%. For CRMA concrete family, this better behavior also occurred when the replacement was 100%. This behavior shows that carbonation depth depends strongly on the chemical composition of the concrete and not only on the physical aspects.
- When the natural aggregate is replaced by 20% of the recycled aggregates from old concrete or old masonry, the resulting recycled concrete will likely present same, and sometimes better, behavior than the reference concrete made with natural aggregates in terms of the properties studied in this investigation. This fact justifies the efforts to use these concretes, which can contribute to the preservation of the environment and can achieve the same final performance with probably less cost than ordinary concretes.

## Acknowledgements

The authors are indebted to the University of São Paulo for its partial support of the research project. Vilma Merli is especially acknowledged for her invaluable help with our English. One of the authors, Salomon Levy, would like to thank to FAPESP, for providing the means to undertake scientific work at the University of São Paulo, and the Technological Research Institute of São Paulo IPT. The opinions and findings expressed here are those of the authors and do not necessarily reflect those of the sponsoring organizations.

## References

[1] E. Wirquin, R. Hahdjeva-Zahaarieva, F. Buyle-Bodin, Utilisation de l'absortion d'eau des bétons comme critères de leur durabilité—Aplication aux bétons de granulats recycles (in French), Mater Struct 33 (2000 July) 403–408.

[2] P.K. Mehta, P.J.M. Monteiro, Concrete Structure, Properties and Materials, PINI, São Paulo, 1994.

[3] P. Helene, P.J.M. Monteiro, Designing concrete mixtures for strength, elastic modulus and fracture energy, Mater Struct 26 (162) (1993 October) 443–452.

[4] ASTM International, ASTM C 270-03b: Standard Specification for Mortar for Unit Masonry, ASTM International, 2003.

[5] ASTM International, ASTM C 39/C39M-03: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, 2003.

[6] ASTM International, ASTM C 642-97: Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, ASTM International, 2003.

[7] RILEM CPC 18, Measurement of hardened concrete carbonation depth, Mater Struct 21 (126) (1988 November) 435.

[8] S.M. Levy, Contribution for durability of concretes manufactured with recycled aggregates from demolished masonry and concrete structures (in Portuguese), PhD thesis, University of São Paulo PCC.USP, São Paulo, 2001.

[9] J. Clifton, Service life prediction, ACI Mater J 90 (6) (1993 November/December) 611–617.

[10] K. Tuutti, Corrosion of steel in concrete, PhD thesis, Cement and Concrete Research Institute, Stockholm, 1982.