# Chloride penetration and strength of recycled aggregate concrete

A.A. Tsoumani [1], N.-M. Barkoula [1], T.E. Matikas [1]

[1]Department of Materials Science and Engineering, University of Ioannina, 45110 Ioannina, Greece
Corresponding author email: anna.tsoumani@gmail.com, tel.: 2651026701/6945855177, fax: 2651111305

**Abstract**

The amount of construction and demolition waste has increased considerably over the last few years. Due to environmental benefits, their use as a source for concrete aggregates has attracted increasing interest from the construction industry. However, the concrete's performance characteristics require reassessment in relation to natural aggregate concrete, especially regarding the durability properties of concrete. Focusing in this area, a research on the chloride penetration of concrete prepared with recycled aggregates was carried out. Two concrete mixes with a target compressive strength of 25 MPa were prepared, at a substitution level 0% and 100% of the total coarse aggregate. Properties of fresh and hardened concrete were determined for both mixtures. Concrete chloride permeability was determined according to the requirements of ASTM C1202, conducting the Rapid Chloride Permeability Test and using the device PROOVE'it©. Regarding the chloride permeability of the concrete specimens, increased permeability was observed when recycled aggregates were used. However, the recycled aggregates' concrete was classified in the same category of chloride permeability, namely medium permeability. Concluding, the use of recycled aggregates as a replacement of natural ones, concerning their effect in chloride permeability, is not prohibitive.

**Keywords**: construction and demolition waste, recycled aggregates, concrete, compressive strength, chloride penetration

## 1. Introduction

Nowadays, it is obvious that natural resources are not inexhaustible elements of the environment, so their use should be managed in such a way that all productive activities leave them intact for future generations. A sector that is very demanding in terms of raw material sources, energy consumption and pollutants production is the construction industry. On the other hand, the amount of construction and demolition waste (C&D waste) has increased considerably over the last few years. A solution for reserving the natural resources and also diminishing the waste disposal sites is the reuse of C&D waste [1]. This material may be used after suitable treatment as recycled aggregate for producing environmentally friendly concrete. However, there is still suspicion concerning the use of inert materials from recycling, especially with regards to their use as concrete aggregates.

Several studies have been carried out using recycled aggregates. However, while studies on the engineering properties of concrete made with laboratory – crushed concrete aggregate [2-6] or demolished concrete aggregates are abound [7-10], only limited data are available on commercial – grade recycled aggregate. Moreover, the existing studies, that are based on commercial – grade recycled aggregate, focus mainly on concrete's mechanical properties [11-14]. Therefore research on the durability properties of concrete, such as chloride penetration, carbonation and freeze-thaw resistance, is almost nonexistent.

However, corrosion of reinforcing steel due to chloride ingress is one of the most common environmental attacks that lead to the deterioration of concrete structures. Furthermore, due to its frequent occurrence and its associated high cost repair has received widespread attention in recent years. Thus, this paper estimates the influence on the properties of fresh and hardened concrete produced by commercially crushed and graded recycled aggregates, focusing on the determination of concrete's chloride permeability.

## 2. Experimental

### *2.1 Materials*

The mixes' consisted of cement, water, fine aggregates, coarse aggregates and superplasticizer, i.e. water reducing agent. Ordinary Portland cement, designated type CEM II was used. The coarse aggregates used in this study included both natural and recycled aggregates. The natural aggregates were crushed limestone sourced from a local quarry, with nominal sizes of 9.5 mm (3/8”) and 25mm (1”). The recycled aggregates were derived from C&D wastes, which had been processed by mechanized crushing and sieving at a C&D waste recycling plant that is located in the industrial area of Thessaloniki, Greece.

The origins of the C&D waste were unknown; therefore, the composition was evidently heterogeneous, depending on the type, age, use and size of the structure it came from. The material contained: pieces of concrete, bricks, ceramic tiles, marble, asphalt and natural aggregates (sand, carved stones, gravel). Besides, it contained a small percentage of: mosaic, wood, plasterboard, plywood, pieces of plumbing parts, plastic parts, metal objects (wires, screws, etc.), cables, paper, dirt and other pollutants. The percentage of each material is presented in Figure 1, showing that the largest part obtained was concrete, as it is the most used construction material nowadays.

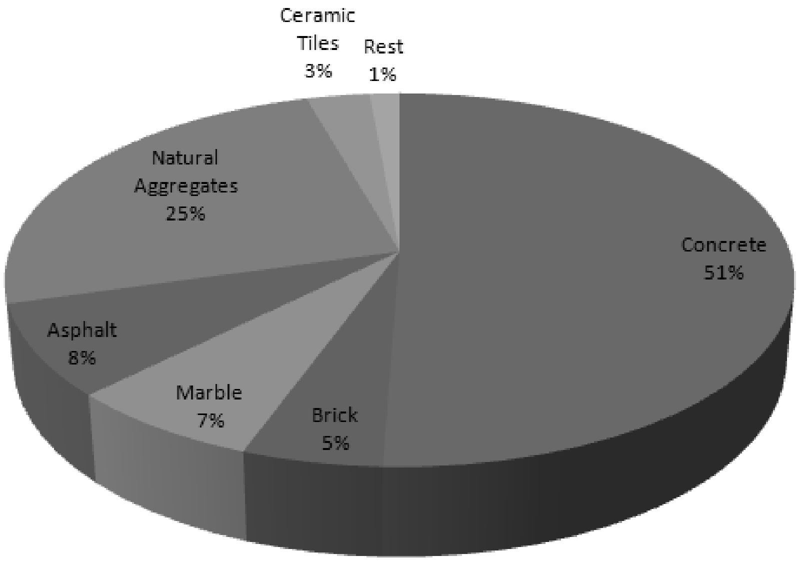


**Fig.1** Construction and demolition waste composition.

Only coarse recycled aggregates with the maximum nominal sizes of 11 mm and 25 mm were used in this study. The recycled aggregates were characterized in accordance with international standards (ASTM or EN specifications).

| **Sieve Designation ASTM E11** | **Sieve size (mm)** | **Fine aggregate** | **Coarse aggregate** | | **Coarse aggregate** | |
|---|---|---|---|---|---|---|
| | | | **Natural** | **Recycled** | **Natural** | **Recycled** |
| | | | **nominal size (mm)** | | | |
| | | | **9,5** | **11** | **25** | **25** |
| | | ***% passing*** | | | | |
| 1 1/2" | 38,1 | 100,00 | 100,00 | 100,00 | 100,00 | 100,00 |
| 1" | 25,0 | 100,00 | 100,00 | 100,00 | 96,17 | 98,73 |
| 3/4" | 19,0 | 100,00 | 100,00 | 100,00 | 65,15 | 84,37 |
| 1/2" | 12,5 | 100,00 | 100,00 | 100,00 | 8,32 | 45,01 |
| 3/8" | 9,50 | 100,00 | 93,20 | 98,45 | 3,34 | 19,35 |
| No 4 | 4,75 | 99,99 | 36,10 | 25,77 | 2,08 | 5,07 |
| No 8 | 2,36 | 86,96 | 2,50 | 1,80 | 1,74 | 3,65 |
| No 16 | 1,18 | 53,35 | 1,50 | 1,26 | 1,53 | 2,70 |
| No 30 | 0,60 | 33,38 | 1,40 | 0,80 | 1,48 | 1,75 |
| No 50 | 0,30 | 22,36 | 1,40 | 0,35 | 1,39 | 0,75 |
| No 60 | 0,25 | 20,57 | 1,30 | 0,27 | 1,37 | 0,58 |
| No 200 | 0,075 | 13,47 | 1,30 | 0,12 | 1,24 | 0,32 |

Table 1 Particle size distribution of aggregates.

The fine aggregates used were crushed limestone sand (nominal size: 4.75mm). Fine recycled aggregates (nominal size: 5mm) were not used in concrete production because of their low quality (sand equivalent value and blue methylene test value were lower than those required). The particle size distribution, water absorption and density of the different types of aggregate are given in Table 1 and Table 2, respectively.

| | **Fine aggregate** | **Coarse aggregate** | | **Coarse aggregate** | |
|---|---|---|---|---|---|
| | | **Natural** | **Recycled** | **Natural** | **Recycled** |
| | | **nominal size (mm)** | | | |
| | | **9,5** | **11** | **25** | **25** |
| **Absorption (%)** | 2,60 | 1,35 | 4,80 | 1,40 | 5,40 |
| **Bulk specific gravity/ saturated- surface -dry ($kg/m^3$)** | 2,52 | 2,56 | 2,36 | 2,60 | 2,39 |

Table 2 Water absorption and bulk specific gravity of aggregates.

*2.2 Concrete mixtures*

The experimental procedure involved the preparation of two concrete mixes with a target concrete quality of C25/30 (28-day cylindrical compressive strength of 25 MPa and 28-day cubic compressive strength of 30 MPa) quality concrete. Several preliminary trial mixtures were proportioned to evaluate water requirements for such a concrete. The first concrete mix consisted exclusively of crushed aggregates (substitution level 0% - reference concrete) and the second one consisted exclusively of recycled aggregates (substitution level 100%). The concretes were produced in an automatic mixing machine, aggregates were used in a dry condition (using an oven), however they were presaturated for 8 minutes in the mixer and brought to room temperature prior to concrete mixing. The proportions of the concrete mixes were designed using the absolute volume method according to ACI 211.1 Standard. Mixture proportion data are given in Table 3. The effective water – cement ratio of all mixtures was the same in both mixtures and equal to 0.5.

| **Mix** | **Replacement Percentage (%)** | **Cement** | **Water** | **Superplasticizer** | **Aggregate** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Fine** | **Coarse** | | | |
| | | | | | | **Natural** | **Recycled** | **Natural** | **Recycled** |
| | | | | | | **nominal size (mm)** | | | |
| | | | | | | **9,5** | **11** | **25** | **25** |
| M1 | 0,0 | 280 | 178 | 1,70 | 931 | 293 | - | 675 | - |
| M2 | 100,0 | 280 | 211 | 1,70 | 931 | - | 279 | - | 620 |

Table 3 Proportion data of concrete mixes ($kg/m^3$).

*2.3 Casting, curing and testing*

Properties of fresh and hardened concrete were determined for both mixtures. In particular, regarding the properties of fresh concrete; workability was measured through slump, using the standard slump test apparatus, according to ASTM specifications (ASTM C143), air content was determined according to ASTM specifications (ASTM C 231) and density of fresh concrete was determined according to EN specifications (EN 12350-6). The properties of fresh concrete were measured immediately after mixing.

For each mix, 6 cubic specimens of 150 mm in size were cast in steel moulds and kept in a mist room at $20^oC$ for 24 h until demoulding. The cubes were then placed in water at $20^oC$. Compression tests took place at the age of 28 days, according to the EN specifications (EN 12390-3), while concrete chloride permeability was determined according to the requirements of ASTM C1202, conducting the Rapid Chloride Permeability Test and using the device PROOVE'it©. All the tests were conducted in the laboratory environment at room temperature of about 20–24 $^oC$.

The Rapid Chloride Permeability Test involved obtaining a 100 mm diameter core sample from the concrete being tested. A 50 mm specimen was cut from the sample. The side of the cylindrical specimen was coated with epoxy, and after the epoxy was dried, all specimens were put in a vacuum chamber for 3 hours. The specimens were vacuum saturated for 1 hour and allowed to soak for 18 hours. After this treatment the specimens were placed in the test device, which is composed of two cells filled with two different types of solutions; the first one is filled with a 3% NaCl solution and the other one with a 0.3N NaOH solution. The system was then connected and a 60-volt potential was applied for specific time period (six hours). Readings were taken every 30 minutes. At the end the specimen was removed from the device and the amount of coulombs passed through the specimen was calculated. Based on the electric charge value, concrete was categorized in degrees of chloride permeability according to Table 4.

| **Charge passed (Coulombs)** | **Chloride Permeability** |
|---|---|
| >4000 | High |
| 2000 – 4000 | Moderate |
| 1000 – 2000 | Low |
| 100-1000 | Very Low |
| <100 | Negligible |

Table 4 Chloride permeability based on charge passed

**3. Results and discussion**

All experimental measurements are presented in Table 5. The results reveal that regarding the properties of fresh concrete, no great deviation is observed. However, the workability and the density of the recycled aggregate concrete are lower than the one of the reference concrete, while the air content is higher. In particular, the workability of the recycled aggregate concrete is lower than the workability of the reference concrete 0.30 cm (4% reduction) which is a result of the angular and elongated shape of recycled aggregates. The air content of recycled concrete is increased by 0.2% (9.5%) compared to reference concrete, due to shape and high porosity of recycled aggregates. Moreover, the density of recycled concrete is 11.60% less than the density of the reference concrete. This reduction is due to the lower specific weight of the recycled aggregates as well as the increased air content in the mixture.

| **Property** | **Substitution level** | |
|---|---|---|
| | **0%** | **100%** |
| workability (cm) | 8,0 | 7,7 |
| air content (%) | 1,9 | 2,1 |
| density (Kg/m$^3$) | 2420 | 2140 |
| compressive strength 28 days (MPa) | 45,0 | 33,0 |
| electric charge passed (Cb) | 3140 | 3810 |
| chloride permeability | moderate | moderate |

Table 5 Experimental measurements.

In advance, using recycled aggregates leads to a reduction of the compressive strength, up to 25%, however. This result is in agreement with the increased percentage of air content of the mixture, which affects the strength and durability of the concrete. However, despite its reduced strength; the recycled aggregate concrete corresponds to C25/30 category concrete. These results were more or less expected due to the physical and mechanical properties of the recycled aggregates [1].

Regarding the chloride permeability of the concrete specimens, increased permeability was observed for the ones of recycled aggregate concrete, as presented in figure 2. However, while the passing electric charge is increased for the recycled aggregate concrete (20% approximately), both concrete types are classified in the same category of chloride permeability, namely moderate permeability, which suggests that the use of recycled aggregates for the production of concrete is not prohibitive.

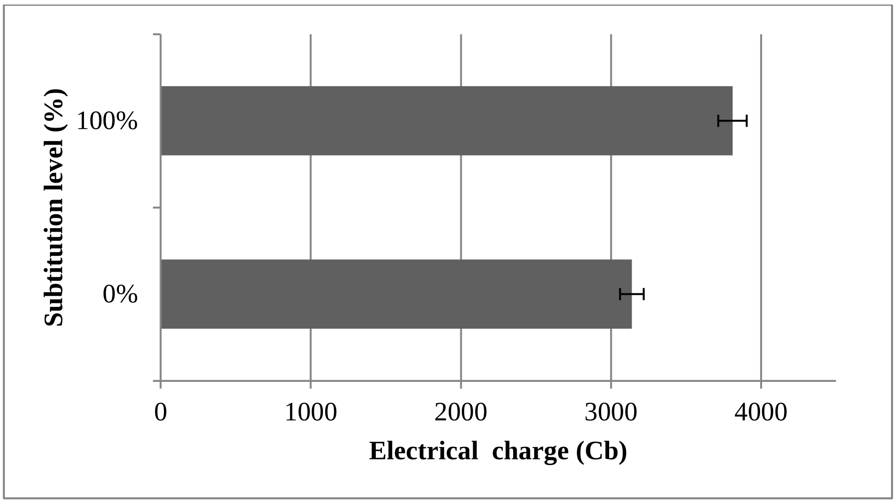


**Fig.2** Test results of Rapid Chloride Permeability Test (PROOVE'it©)

## 4. Conclusions

In the current study, crushed coarse aggregated were fully replaced by recycled ones and their influence on the properties of fresh and hardened concrete was assessed, focusing on concrete's chloride permeability. From the obtained results the following conclusion can be drawn:

The effect of using recycled aggregates on the properties of fresh concrete is negligible on account of the shape, porosity and specific weight of the recycled aggregates. Moreover, the use of recycled aggregates causes a decrease in compressive strength and an increase in chloride permeability. However, the produced recycled concrete corresponds to C25/30 category and moderate permeability concrete. Summarizing, recycled aggregates obtained from a C&D waste sorting facility have potential to be used as concrete aggregates, even with total substitution of the coarse aggregates. Furthermore, on terms of chloride permeability recycled aggregates can be used as concrete aggregates in a safe and sustainable way.

## 5. Acknowledgements


The authors would like to thank "Anakiklosi Adranon Macedonias" (Macedonia's aggregates recycling company) for providing the samples of recycled aggregates and especially Mr. Christoglou for his useful advice. The authors also wish to acknowledge Domylco Ltd. for providing the superplasticizer water reducing agent CHEMIUM-274. Finally we would like to thank TITAN Group and Mr. Leptokaridis in particular for their advice and experimental assistance.


## 6. References


[1] A. A. Tsoumani, N.-M. Barkoula, T. E. Matikas: Recycled aggregate as structural material. Waste Biomass Valorization (2015).doi: 10.1007/s12649-015-9385-0

[2] Ajdukiewicz A., Kliszczewicz A.: Influence of recycled aggregates on mechanical properties of HS/HPC. Cement & Concrete Composites. 24, 269–279 (2002)

[3] Arm M.: Self-cementing properties of crushed demolished concrete in unbound layers: results from triaxial tests and field tests. Waste Management. 21, 235-239 (2001)

[4] Zega C. J., Villagra´n-Zaccardi Y. A., Di Maio A. A.: Effect of natural coarse aggregate type on the physical and mechanical properties of recycled coarse aggregates. Materials and Structures. 43, 195–202 (2010)

[5] Eguchi K., Teranishi K., Nakagome A., Kishimoto H., Shinozaki K., Narikawa M.: Application of recycled coarse aggregate by mixture to concrete construction. Construction and Building Materials. 21, 1542–1551 (2007)

[6] Zhang X., Deng S., Deng X., Qin Y.: Experimental research on regression coefficients in recycled concrete Bolomey formula. J. Cent. South Univ. Technol. s1−0314−04 (2007)

[7] Etxeberria M., Marı´ A. R., Va´zquez E.: Recycled aggregate concrete as structural material. Materials and Structures. 40, 529–541 (2007)
[8] Tam V., Tam C.M.: Diversifying two-stage mixing approach (TSMA) for recycled aggregate concrete: TSMAs and TSMAsc. Construction and Building Materials. 22, 2068–2077 (2008)
[9] Tu T.-Y., Chen Y.-Y., Hwang C.-L.: Properties of HPC with recycled aggregates. Cement and Concrete Research. 36, 943–950 (2006)
[10] López-Gayarre F., Serna P., Domingo-Cabo A., Serrano-López M.A., López-Colina C.: Influence of recycled aggregate quality and proportioning criteria on recycled concrete properties. Waste Management. 29, 3022–3028 (2009)
[11] Xiao, J. Z. and Li, J. B.: Study on relationships between strength indexes of recycled concrete (in Chinese). Chinese Journal of Building Material. 9, 197–201 (2005)
[12] Tang J.: Preliminary study on compressive strength of recycled aggregate concrete (in Chinese). Sichuan Building Science. 33, 183–186 (2007)
[13] Jin, C., Wang, X. P., Akinkurolere O. O.: Experimental research on the conversion relationships between the mechanical performance indexes of recycled concrete (in Chinese). Chinese Concrete Journal. 11, 37–39, 49 (2008)
[14] Evangelista, L. and de Brito, J.: Mechanical behavior of concrete made with fine recycled concrete aggregates. Cement and concrete composites. 29, 397-401 (2007).