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A Case Study on The Mechanical and Durability Properties of a Concrete Using Recycled Aggregates

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Abstract

In Morocco, Recycled Aggregate Concrete (RAC) is not promoted unlike developed countries like France, Canada, US and many others. This article aims to present a Moroccan study related to the characterization of RAC and compare it with several studies all over the world. It focuses on compressive strength as the main mechanical characteristic and the porosity as the physical property that affects durability. The protocol is based on crushing concrete from demolished building and producing aggregates that are used in making experimental samples of RAC with different percentages of replacing Natural Aggregates (NA) by recycled ones. The first part of experimental study is to determine compressive strength of these samples after 7, 21, 28 and 90 days of confectioning it. Test results prove that above 25% of replacement level, the compression drops considerably and the Recycled Aggregates (RA) can't replace the naturel ones. The second part of studies focuses on studying porosity as indicator of durability according to the performance approach. It concludes that the RAC may be used in a construction with a required life of 100 years specially building and roads. For high standards constructions or construction in a specific environment, more studies should be done.

Keywords: Concrete; Natural Aggregates; Recycled Aggregates; Replacement Percentage.

1. Introduction

Recycling aggregates is increasingly valuing in order to struggle with the shortage of natural resources and to comply with the sustainable development requirements. Even if there are no law or standards governing the use of RA in Morocco, several studies and researches are in progress to determine the influence of the replacement of NA by recycled ones on the concrete characteristics. This article, part of a doctoral study in civil department at Mohammadia School of engineers-Morocco, aims to characterize a concrete manufactured based on a crushed old concrete from a demolished building. The study of the concrete is based on two parameters:

- Compressive strength of concrete samples as an indicator of mechanical properties;
- Porosity as a physical parameter that influences durability based on the performance approach.

The main objective of the study is to determine the percentage of replacement of NA by recycled ones appropriate to an acceptable concrete from the technical point of view. The protocol of experimental tests will focus on studying the compressive strength of concrete samples at different ages and different percentage replacements than determining the amelioration on this mechanical property when using additives specially adjuvants and finally testing the porosity of concrete to conclude about its durability.

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2. Literature Review

The interest on recycled materials as a sustainable replacement of NA has grown this last decade due to their respect of environmental and reuse requirements. RAC is thus promoted as an innovative solution that combine innovation, respect of the environment and reuse of materials without harming technical and sustainability requirements [1-3]. Many studies have been done to determinate its properties comparing to concrete using NA. A wide variability is found in mechanical and durability results and so the use of RAC is restricted to non-structural applications such as road sub-base materials and landfilling materials [4].

The study of RAC characteristics must be preceded by defining RA properties. Based on many studies, RA have higher water absorption, lower density, lower resistance to fragmentation, more pores and an irregular form compared to NA [4, 5]. This decrease in properties affects directly RAC properties specially with high replacement percentage of NA by RA.

The compressive strength is the most effective characteristic which affects all mechanical, durability and others properties [6, 7]. From a compressive strength point of view, using RA is accepted up to 20-30 % replacement of NA [8-11], 25% is the optimal replacement ratio according to Etxeberria et al. [11]. Above this value, the compressive drops considerably: 25% drop for 100% replacement by Bai et al. [6], 30-40% drop by Kazmi et al. depending on the quality of the original aggregates [5]. Even if the modulus of elasticity, tensile strength and flexural strength studies prove that their drops have almost the same trend as compressive strength results [7, 12, 13], the loss of compressive strength of concrete is more sensitive to the incorporation of RA than the others properties [6].

Durability performances: deformation (drying shrinkage), impermeability, chloride penetration resistance, carbonation resistance, frost resistance and alkali aggregate reaction of RAC are also weaker than NAC ones [3, 8, 9, 14]. Thomas et al. even noted that increases decrease with the increase of the degree of replacement for RAC [9]. The open porosity, sorptivity and rapid chloride permeability test values of RAC reach their maximum when percentage of NA replacement is 100% [14]. Density value decreases 5% for 20% replacement percentage of NA by RA and 20% for 100% replacement [9], Rao et al. reported 7.37% water absorption for concrete with 100% RA and 6.54% for concrete with 50% RA [3].

Some other researcher's conclusions relative to RAC durability are: Impermeability is 2.47 times higher by immersion and 1.7 times by capillarity than that of a corresponding NAC specimen according to Guio et al. [15], Kou & Poon found 9.5% lower resistance to chloride permeability for 100% RCA mixture [10].

Many methods are proposed to improve RAC properties such as:

- Adjusting water-cement ratio [16].
- Removing adhered mortar. In fact, adhered mortar affects many properties specially durability and strength because of its high permeability [17].
- Adding pozzolanic materials or water repellent to improve cement matrix [18].
- Adding mineral admixtures such as fly ash and silica fume. The use of fly ash reduces the permeability and improves the workability of RAC. Silica fume, due to its small size and its large surface area, improves the microstructure of concrete creating a denser matrix [19].
- Using new method of mixing method of RAC such as two or three stage mixing methods [20].
- Using physical and/or chemical methods to enhance RAC without removing adhered mortar essentially encapsulation and impregnation by a foreign chemical [21]. These techniques may have inconvenient like reducing the compressive strength of RAC [17, 18, 22, 23].

3. Research Methodology

The experimental protocol aims to characterize the RAC and to determine the percentage of replacement of NA by recycled ones that respects the technical requirements. These tests also focus on enhancing the mechanical and durability properties of RAC.

3.1. Experimental Tests Related to Compressive Strength of RAC

The objective of the study is to determine the RAC compressive strength, considered as the main mechanical characteristic. The test is done according to the NF EN 12390-3 standard [24]. The concrete tested is a usual concrete, used in all types of building and roads without any specific requirements. It should have a compressive strength of 25 MPa after 28 days of confecting it and an average slump of 7-9 cm after mixing it.

The concrete formulation using dreux-gorisse method [25] is:

Table 1. The concrete formulation for 1 m^3 of concrete

Constituent	Mass (kg)	Volume (m^3)
Water	190	0.2
Cement	350	0.3
Sand	473	0.3
Gravels [5-12.5] mm	376	0.15
Gravels [12.5-31.5] mm	573	0.2

To determine the effect of the replacement percentage on concrete characteristics, several rates are proposed: 0, 25, 50, 75 and 100%. The choice of proportions is based on varying over the entire field from 0 to 100%. The Figure 1 shows steps of concrete preparation, specimen conservation and crushing.

Figure 1. Concrete specimens preparation steps: (a) Concrete and test tubes preparation; (b) Conservation of test specimens; (c) Crushing concrete tubes

In order to improve the compressive strength results for different replacement levels, the addition of adjuvants is tested. The chosen additives are plasticizers because of their capacity to reduce the water requirement of aggregates and thus improve the quality of the concrete. Three products from SIKA- MAROC are tested:

- Plasticizer (water reducer) named BV40.
- Superplasticizer or high-water reducer named Sika ViscoCrete Tempo 10M.
- New generation of superplasticizer: SikaFluidR (SFR).

Adjuvants are used in replacement of cement. The ratio of replacement tested will be chosen between 0.5 and 1.5%.

3.2. Experimental Tests Related to RAC Durability

In order to validate the possibility of replacing an ordinary concrete by a RAC, additional technical studies must be carried out essentially a durability study. The technical validation of the RAC depends on several elements mainly the type of project, its location, external conditions and others. The performance approach is a new developed protocol that has been developed recently to characterize a concrete from a durability point of view [26]. This approach focuses on many criteria to choose parameters to study essentially the type of project which affects the required age. For an ordinary building or road, the required age is 50 years, it might reach 100 years for special buildings or engineering works. For civil developed projects like bridges, the required life exceeds 100 years.

The second parameter is environment type. It depends on the project locations (dry, wet, exposed to sea salts, etc.). For our project, we will focus on a building with a required life of maximum 100 years located in a usual environment.

Based on the performance approach, the requirements of the concrete to be durable are summarized in the table below.

Table 2. Durability's criteria for building based on the performance approach (P: porosity %)

50 -100 Building and civil engineering works	30- 50 Building	< 30	Required life Project Category / Environment type
P < 14	P < 16	P < 16	- Dry and very dry (RH <65%) - Permanently wet (including immersion in fresh water)
P < 14	P < 16	P < 16	Wet, rarely dry (RH> 80%)
P< 14	P < 15	P < 16	Exposure to sea salts or deicing, but not in direct contact with seawater with law $[Cl^-]$

Porosity is, thus, the parameter to study to judge concrete's durability. It is calculated according to NF P18-459 standard [27] using the following equation:

$$£= (Mair-Msec)/ (Mair- Meau) \times 100 \quad (1)$$

The test is based on the inhibition of the test sample in a constant pressure chamber. The test piece is then placed in a hydrostatic balance suspension system and its weight Meau is calculated. After removing the test tube from the water and wiping it quickly to remove surface water without removing water from the pores, Mair is calculated as the weight of tube with intern water. At the end of the trial, the specimen is placed in the oven to remove the interstitial water and thus to determine Msec as the weight of solid phase only.

4. Results and Discussions

4.1. Experimental Tests Related to Compressive Strength of RAC

The compressive strength tests are done with several percentages of replacement level: 0, 25, 50, 75 and 100% to define the drop evolution of strength based on the formulation used. The samples are crushed after 7, 21, 28 and 90 days of confectioning it. These days will show the evolution in time of the strength for every percentage of replacement. The table below resume the tests results.

Table 3. Mechanical strengths obtained at different ages (MPa)

Percentage of replacement of NA by RA / Day of crushing	7 days	21 days	28 days	90 days
0% RA (Reference)	17	23	25	26
25% RA	16	20	23	25
50% RA	15	18	18	20
75% RA	14	17	17	19
100% RA	14	15	15	18

To study the evolution of strength in time for every percentage level, a graph is established for every replacement level evolution between 7, 21, 28 and 28 days.

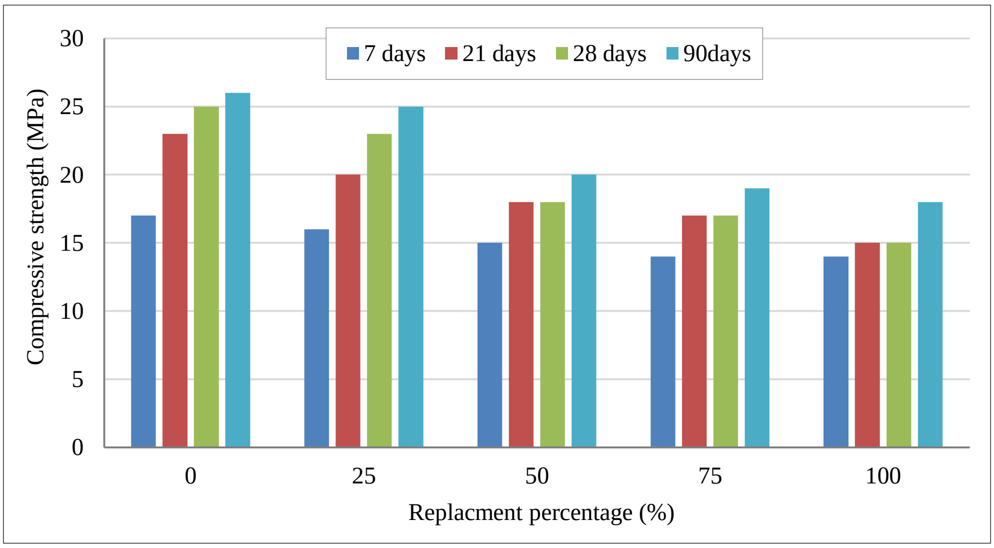

Figure 2. Compressive strength for different percentage replacement after 7, 21, 28 and 90 days of confection

For all replacement values, the compressive strength increases over time. The slope of evolution curve is different: For 0% replacement level for example, the compressive at 7 days is 57% of final strength at 90 days, for 25% it is 65% and above 50% of replacement level, we attend more than 75% of final compression at 7 days. The determination of the effect of replacement percentage in the compressive strength at several ages will be studied based on the graph below. The graph shows that, for all ages, the compressive strength drops with the increase of replacement level.

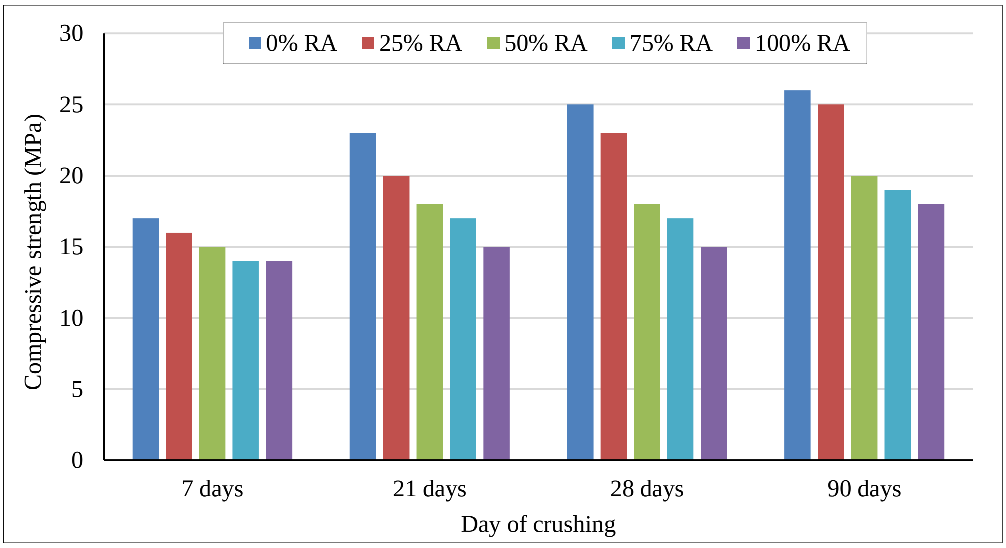

Figure 3. Compressive strength for different percentage replacement at the same age (7, 21, 28 and 90 days)

For 25% replacement level, the drop of compressive strength at 28 days is 8% comparing to the reference value (25Mpa) attended by the reference samples (0% RA), which makes this replacement level acceptable from a technical point of view. For 50% and more, the drop is more than 30%. The replacement isn't authorized from a technical point of view. In order to improve these results, the ad of adjuvants is tested. The second section concerns then, compression tests on advanced concrete formulas. It aims to improve the strength of concrete for replacement percentages above 25%, ideally 50%. The tests concern the determination of an optimal combination between the choice of plasticizer to adopt and the percentage of replacement of the cement.

This phase is subdivided into 3 stages:

- Determination of the effect of adding an additive on compressive strength for various percent replacement.
- Use of several types of additives in order to conclude on the effect of the additive chosen.
- Testing several percentages of cement restitution by the admixture in order to choose the replacement percentage that gives the best result. The percentages to be tested were chosen by referring to the recommendations on each product sheets.

For the mixture with additives, we used three products from SIKA- MAROC:

- Plasticizer (water reducer) named BV40.
- Superplasticizer or high-water reducer named Sika ViscoCrete Tempo 10M.
- New generation of superplasticizer: SikaFluidR (SFR).

First Step: Determining the Effect of the Additive on the Compressive Strength of RAC with Different Percentage of RA

Table 4 summarizes the results of compressive strength tests done for several test specimens with percentages covering the entire field from 0 to 100% with and without plasticizer. The test is done after 28 days of confection. The additive used is the plasticizer with 1% restitution of cement.

Table 4. Compressive strength results for RAC with plasticizer and different percentage of recycled aggregates

Percentage of RA in RAC	Compressive strength at 28 days (MPa)	
	Without plastisizer	With plastisizer
25%	23	24
50%	18	21
75%	17	20
100%	15	19

These tests adhere to the results of concrete without additives where compression decreases with increasing replacement of NA by RA.

Second Step: Choosing the Additive Giving the Best Strength

This step consists on testing several generations of plasticizers. A plasticizer with an average water requirement reduction rate of 5 to 15%, a superplasticizer which can reduce water requirement by 30% and a new generation super-plasticizer which in addition to its high reduction in water requirement, allows other more advanced performances: very long maintenance of maneuverability, pumping over long distances, adaptable with all the consistency of concrete. Tests are done on RAC with a percentage of replacement of 50% using 1% as a ratio of restitution of cement. Results are summarized in Table 5.

Table 5. Compressive test results on RAC at 28 days for RAC with different additives

Type of additive	Compressive strength at 28 days (MPa)	Percentage of amelioration of strength at 28 days
-	18	-
BV40	23	25%
Tempo 10 M	21	19%
SFR	17	-08%

Compressive strength improves with the addition of the plasticizer as well as the superplasticizer. The new generation superplasticizer gives a lower result. This can be interpreted as a poor interaction with the aggregates and their attached cement paste. We can conclude that the quality of aggregates is conform to a plasticizer because of their low need of extra water to be 100% pre-hydrated.

Third Step: Choosing the Optimal Percentage of Replacement of Cement that gives the Better Strength

The effect of adding an adjuvant depends mainly on the rate of its use. As noted on the technical data sheet of the plasticizer [28], the dosage chosen should be between 0.2 and 1.5% of the binder weight. To choose the optimum value, comparison tests are carried out for three values: 0.5% as minimum value, 1.5% as maximum value and 1% as average value. The test results are summarized in the table 6 below. Notice that the plasticizer is the additive used and tests were done on RAC with 50% replacement ratio.

Table 6. Compressive strength results for RAC with different percentage of additive

Type of plasticizer	Percentage of the plasticizer	Compression at 28 days (MPa)
Tempo 10M	0,5%	20
	1,0%	21
	1,5%	16

Tests conclude that 1% is the optimum value for restitution. Beyond this value the compression drops.

4.2. Discussion about Mechanical Test Results

These tests aim to characterize RAC from the compressive strength point of view and compare its characteristics with NAC ones. The first study phase demonstrate that the compression decreases with the increase of the restitution rate and that the optimum replacement percentage of NA by RA is around 25%. The compressive strength drop is insignificant (8%). This is in line with the conclusions of the majority of researches done in this direction that found an optimal replacement percentage between 20 and 30 %.

Beyond 50%, the compression drop exceeds 30% compared to NAC. Thus, above 50% as replacement level, the use of RA is not recommended in concrete. The second study phase concerns improving the quality of a concrete with 50% RA by adding an additive. Tests demonstrate that the use of plasticizer with a cement replacement rate of 1% is the ideal combination to improve strength. The drop improves from 30 to 8%. Researchers propose, apart from the addition of adjuvants, several methods of improving the compressive strength of concrete such as sorting demolished concrete and choosing the good quality only or removing adhered mortar [4].

4.3. Durability Characterization of RAC

As exposed above, the study of concrete durability will be done based on the porosity test results. The test was done respecting standards and the results are resumed in the Table 7 below. With £: The porosity of hardened concrete (%).

Table 7. The porosity experimental results

Replacement percentage	M_{sec}(g)	$M_{air}(g)$	M_{eau}(g)	Porosity test results (%)	Porosity value chosen (%)
100%	2322,2	2464,1	1444,8	13,92	13,85
	2318,7	2459,4	1442,5	13,83	
	2310,3	2450,7	1434,8	13,82	
75%	2324,5	2465,6	1430,1	13,63	13,59
	2298,4	2439,9	1415,8	13,82	
	2298,3	2434,8	1410,9	13,33	
50%	2263	2423	1240,5	13,53	13,363
	2271,6	2429,4	1247,7	13,35	
	2284,1	2440,8	1254,3	13,20	

The porosity increases with the increase in the rate of recycled aggregates. This is justified by the presence of two layers of cement: the new cement paste created by the water + cement mixture as well as another layer of old cement enveloping natural aggregates. The determination of the conformability of concrete from a durability standpoint depends on several factors essentially the probable life of the project, which depends on the type of the project, and external conditions of the project. Based on the performance approach and within the framework of the thesis project which consists of using concrete in an ordinary building in an ordinary environment, the concrete complies with conditions of the approach for all constructions with a lifespan of 100 years.

5. Conclusion and Future Work

This article summarizes all the tests carried out as part of a thesis on the characterization of recycled aggregates. These tests can be divided into 2 parts. The first part of tests is related to the mechanical characterization based on compression strength tests, the main conclusion is that the compressive strength depends on the percentage of replacement. It decreases with the increase in the percentage of recycled aggregates. Beyond 25% replacement, the resistance drops considerably and the use of recycled aggregate concrete is not recommended in structural elements. The ad of plasticizer improves strength values and the replacement level might increase to 50% when replacing 1% of cement by plasticizer.

The second part focuses on testing the porosity of RAC as indicator of its durability according to the performance approach. The test concludes that for a building with a required life of 100 years or less located in an ordinary environment: Dry, Wet or exposed to sea salts but without being in contact with it, our RAC is conform to the durability criteria.

The next step of research should focalize on an economic study of replacing naturel aggregates by recycled ones depending on several conditions (distance between the old building, the crushing area and the project, the quantity of concrete produced by recycled aggregates and the quantity needed for the project, etc.).

6. Declarations

6.1. Author Contributions

Conceptualization, K.N.; methodology, K.N.; validation, T.C.; writing—original draft preparation, K.N.; writing—review and editing, K.N.; supervision, K.N. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in article.

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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