INFLUENCE OF PROPORTIONING CRITERIA ON RECYCLED CONCRETE PROPERTIES

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ABSTRACT

This paper presents the results of experimental research using concrete produced by substituting part of the natural coarse aggregates for recycled aggregates from concrete demolition. The influence of the following factors has been determined: the percentage of replacement, the strength and workability of the concrete to be produced, the amount of declassified and source of aggregate, the granular structure of the concrete and the replacement criteria. The properties analyzed in the recycled concretes were: density, absorption, compressive strength, elastic modulus, amount of occluded air, penetration of water under pressure and splitting tensile strength.

A highly simplified test program was designed in order to make the number of tests viable whilst guaranteeing the reliability of the conclusions. Instead of making 576 mixtures that correspond to a complete tests plan, it was only made 27 mixtures according to L27 modified orthogonal array devised by Taguchi to experiments design.

The type of aggregate and the percentage of replacement were the only factors that showed a clear influence on most of the properties. If the water-cement ratio is kept constant and the loss of workability due to the effect of using recycled aggregate is compensated for with additives, the percentage of replacement of the recycled aggregate will not affect the compressive strength.

1. INTRODUCTION

Society has been encouraging environmental policies for the last decades aimed to reduce the degradation of the planet. However, the construction and demolition wastes (C&DW) generated in Spain have been rising significantly from 12.8 million tons in 1999 [1] to 34.8 million tons in 2007 [2]. Previous studies [3] [4] [5] [6] [7] have proven that coarse recycled concrete aggregates can be used in the production of conventional concrete. Under the Second National Plan of C&DW drawn up in Spain, different studies are being carried out with the purpose of being able to reuse concrete construction waste in the production of a new structural concrete called recycled concrete [8] [9] [10] [11] [12]. This paper has been written in accordance with this policy strategy.
This study determines which factors related to the selection of the materials, the dosification and the target quality of the recycled concrete influence its characteristics. The study also highlights those factors which do not have any significant influence. (See 2.1)

The most important aspect of this research lies in the wide range of factors whose influence has been analyzed. Some of them, such as the granular structure of the recycled concrete or the substitution criteria, have not been taken into account in previous studies.

It is also important to underline the statistical approach used, which is highly efficient when compared to other studies in this field but which nevertheless guarantees a rigorous analysis of results. In this study the levels of all of the factors have been varied simultaneously as opposed to varying them one by one. The high number of factors makes it impossible to consider the variation of all the factors individually. It would not be feasible to develop the test program fully, taking into account all the factors. The reduction in the number of combinations to test was based on solid statistical foundations [13] [14] and did not imply any decrease in the scientific rigor of the proposal.

2. APPROACH OF THE EXPERIMENTAL PROGRAM

Experimental research using concrete produced by substituting part of the natural coarse aggregates for recycled ones proceeding from concrete demolition was carried out.

The influence of the following factors on the properties of the recycled concrete was studied: the quality of recycled aggregates, the target quality of the elaborated concrete (compressive strength and workability), the percentage of replacement and the replacement criteria. The selection criteria and levels studied are presented in 2.1.

The highly simplified test program used in the experiments is shown in 2.2.

The properties of the recycled concrete have been stated according to the test program that is presented in 2.3.

2.1. Factors and levels analyzed

a) The quality of the recycled aggregate was analyzed using two recycled aggregates from different sources (OV; MA) and of different quality (table 1). Figure 1 presents the sieve distribution of the recycled aggregates used. The granulometric distribution of the aggregates and in particular the amount of declassified (size fractions smaller than 4 mm.) determines the characteristics of the concrete. This influence was analyzed by using reconstituted aggregates. These were obtained by mixing the original coarse fraction of recycled aggregate with the required quantity of declassified from the same origin in order to obtain the amount of declassified required. Three levels of declassified were studied: (0%, 5% and 10%). In order to maintain exactly the same original granulometry in each mix, the reconstitution of the recycled aggregates was carried out by weighing the quantities corresponding to each of the granulometric proportions separately and subsequently adding them to the mixer. These proportions had been previously separated using an industrial sieve. The required percentage of declassified was also added.

b) The target quality of the recycled concrete was analyzed by using as a reference two types of base concrete commonly used in building and civil engineering: One concrete type was
identified as "C25" with 275 kg/m$^3$ of cement and a water-cement ratio of 0.60, which is usually used in buildings. The second concrete type was identified as "C35" and had 375 kg/m$^3$ of cement and a water-cement ratio of 0.50, as is usually used in civil engineering projects. Cement III / A 42.5 N / SR [16] was used in both cases as this is the cement which is habitually used in the concrete plants which collaborated in the experimental part of this study. The water-cement ratio was calculated taking into account all the water, including that already absorbed by the aggregates.

Two levels of workability were considered for each type of concrete: Slump equal to 80 mm and slump equal to 130 mm. In Spain, both in building and in civil engineering projects, a slump of S2 (50 to 90 mm) is normal. In this study a slump towards the top of this range was used (80 mm). The second slump considered (130 mm) is in the middle of the S3 slump range (100 to 150 mm). The targeted workability was obtained by using 0.86 kg/m$^3$ of water reducer Pozzolith 370 N$^®$ and a variable proportion of high range water reducer Glenium Sky 511$^®$ for each mixture.

The influence of the granular structure of the concrete was analyzed by adjusting the mixture of solids (cement and aggregates) to three reference curves. Our aim was to analyze how the choice of granulometric curve when mixing the aggregates affects the properties of the concrete. The three curves are based on the Bolomey parabola[17] which is one of the granulometric curves of reference most used in the dosification of concretes:

- Fine sieve continuous curve (CF) \( a = 16 \)
- Coarse sieve continuous curve (CC) \( a = 11 \)
- Discontinuous curve (D) \( a = 12 \), removing the fraction 4/8 mm.

The adjustment of the mixture curve to the theoretical curve was carried out using the method of least squares.

c) The percentages of replacement were: PR 0%; 20%; 50% and 100%.

d) Two replacement criteria were analyzed:

   *Simple Replacement (SR).* The corresponding percentage of natural coarse aggregate was replaced by an identical volume of recycled aggregate, reconstituted according to 2.1.a.

   *Compensated Replacement (CR).* Once the volume of the reconstituted recycled aggregate was defined, its declassified portion replaces the same volume of sand. The rest of the recycled aggregate replaces natural coarse aggregates.

In both cases, the natural coarse aggregate fraction replaced was distributed among the two natural coarse aggregates according to its proportioning in the original mixture.
Table 1. Aggregates properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Dry density (kg/m³)</th>
<th>Absorption 24h (%)</th>
<th>L.A. Coefficient (%)</th>
<th>Adhered mortar (%)</th>
<th>Declassified content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcareous gravel (8/20 mm)</td>
<td>2680</td>
<td>0.27</td>
<td></td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Calcareous gravel (4/14 mm)</td>
<td>2690</td>
<td>0.22</td>
<td></td>
<td>26.4</td>
<td></td>
</tr>
<tr>
<td>Recycled (OV) (4/20 mm)</td>
<td>2200</td>
<td>5.00</td>
<td>37.2</td>
<td>34.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Recycled (MA) (4/20 mm)</td>
<td>2360</td>
<td>3.80</td>
<td>33.1</td>
<td>23</td>
<td>1.5</td>
</tr>
<tr>
<td>Calcareous sand (0/4 mm)(*)</td>
<td>2680</td>
<td>0.23</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Silica sand (0/4 mm)(*)</td>
<td>2630</td>
<td>0.07</td>
<td></td>
<td></td>
<td></td>
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</table>

(*) The sand used was obtained by mixing 85% of limestone sand and 15% Silica sand.

Figure 1. Aggregates sieve distribution.

2.2. Experiment Design

A complete test plan to analyze all possible combinations of such an elevated number of factors at all levels would consist of 576 tests. Thus, for the study, a highly simplified test program was designed using the orthogonal array L27 devised by Taguchi 1988 to make the reliability of the conclusions compatible with a viable number of tests. This made it possible to reduce the number of tests to 27 and to detect the influence of the factors on each property. Simple effects were identified and second-order effects were excluded without any loss of scientific rigor in the test [13] [14]. Table 2 shows the 27 tests planned from the modified orthogonal array L27 [18].
2.3. Testing program

Two mixes were elaborated with each of the 27 combinations: “mix A” and “mix B”. In each one, the slump test was carried out [19] and 6 cylindrical specimens of 150 x 300 mm were prepared. In “mix B” a test to determine the amount of occluded air was also carried out [20]. The two mixes were identical. The mix was duplicated in order to make the experiment more reliable and also to overcome the limited volume of the mixer used and make it possible to extend the study to other properties.

All cylindrical specimens were unmolded 24 hours after casting and then cured until test time in a chamber at 20ºC and a relative humidity higher than 95%.

At the age of 28 days, the densities of all specimens were determined [21] and the compressive strength was determined in three specimens of each mixture [22]. The elastic modulus was determined in three specimens of “mix A” [23]. The absorption [24], penetration of water under pressure [25] and splitting tensile strength [26] were determined in three specimens of “mix B”.

The reliability of the experiment regarding density and compressive strength increased as a result of the tests being duplicated.
Table 2. Combinations tested.

<table>
<thead>
<tr>
<th>Test</th>
<th>Type of aggret.</th>
<th>% of replace.</th>
<th>Declassif. content</th>
<th>Type of sieve curve.</th>
<th>Base concrete</th>
<th>Targeted slump cm</th>
<th>Replace. criteria.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OV</td>
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<td>0</td>
<td>CF</td>
<td>C35</td>
<td>8</td>
<td>SR</td>
</tr>
<tr>
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<td>MA</td>
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<td>5%</td>
<td>CC</td>
<td>C25</td>
<td>13</td>
<td>CR</td>
</tr>
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<td>10%</td>
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<td>SR</td>
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<td>CF</td>
<td>C35</td>
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<td>SC</td>
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<td>10%</td>
<td>CC</td>
<td>C35</td>
<td>13</td>
<td>SR</td>
</tr>
</tbody>
</table>

3. ANALYSIS OF RESULTS

The criteria used for designing the experiment make analysis of variance (ANOVA) an efficient tool to study the influence of all factors, at the various levels taken into account, on each of the properties. For this purpose the application Statgraphics Plus version 5.1 was used.

The mechanical properties of recycled concrete obviously depend on its base concrete (C25 or C35). In order to avoid obvious conclusions, the studies of the influence on the compressive strength ($f_c$), elastic modulus ($E_c$) and splitting tensile strength ($f_{ct}$) were applied to the respective typified values $f_{c,tip}$, $E_{c,tip}$ and $f_{ct,tip}$ according to the equations:

$$E_{c,tip} = E_c / (f_{cm,0%})^{1/3} \quad ; \quad f_{c,tip} = f_c / f_{cm,0%} \quad ; \quad f_{ct,tip} = f_{ct} / (f_{cm,0%} - 8)^{2/3}$$
where $f_{cm,0\%}$ is the mean value of the compressive strength of the base concrete with no substitution of natural aggregate for recycled aggregate.

In designing the experiment, one of the factors chosen was the target resistance of the recycled concrete. This factor has two levels: one corresponding to 25 MPa (C25) and the other to 35 MPa (C35). Given that now the output variables of the ANOVA are compression strength ($f_c$), the elasticity modulus ($E_c$) and the indirect tensile strength ($f_{ct}$), there is no doubt that the target resistance factor will bear a great influence on the values obtained in the tests for these properties. In order to overcome this problem and with the aim of comparing the results of the 27 tests for compressive strength, for elasticity modulus and for tensile strength, regardless of the target resistance, the output variable was typified by dividing the value obtained in the test by the mean resistance in the mixes with the same target resistance and with no substitution of recycled aggregate. This makes it possible to calculate $f_{c,tip}$, $E_{c,tip}$ and $f_{ct,tip}$ using the aforementioned equations.

The factors analyzed – declassified content, base concrete, objective workability, sieve reference curves or replacement criteria – have no influence or their influence on the property value is of no importance, except in two cases. Firstly, the declassified content and the targeted workability have a slight influence on the splitting tensile strength and its effects are important. Nevertheless, the influence of the percentage of replacement is greater and in this case the property showed great variability, making it difficult to justify the analysis. Furthermore, it has been found that concretes C35 have a higher absorption than concretes C25, although concretes C35 have a higher content in cement and a lower water-cement ratio. This has been attributed to a more refined porous structure.

Penetration of water under pressure is a property in which the ANOVA did not detect any influential factor. This is because the variability of the test is, in itself, much higher than the analyzed influences.

Finally, it is clear that the type of recycled aggregate and the percentage of replacement are the factors that clearly influence most of the properties. However, their effects can vary considerably, depending on the property analyzed.

Density is hardly affected by the type of aggregate and even when the replacement is 100%, the density variation will not exceed 5%.

However, as the percentage of replacement increases, the absorption and the occluded air content will clearly increase, because they are very sensitive. Figures 2, 3, 4 and 5 show the LSD intervals (Least Significant Difference) for these features and factors. Although, in the case of occluded air, the percentages of variation of the mean values are higher, LSD intervals are superimposed and the rising trend is clearly defined only for replacement percentages above 50%. However, absorption shows a clear dependence on both factors. The adhered mortar has a high absorption, so if concretes have a high amount of recycled aggregates and the quality of the recycled aggregates is low, absorption will increase, exceeding values found in conventional concrete by almost 50%. But even if the amount of recycled aggregates is low (20%), absorption increases significantly (24.6%).

It was verified that concretes that had been prepared with a higher quality of recycled aggregates (MA) had more compressive strength than concretes made with OV recycled aggregates (Figure 6) However, as the percentage of replacement increased, the typified mean
compressive strength changed slightly (Figure 9). This is because in this study the total water-cement ratio was constant, so if the content of recycled aggregates with a high absorption level increased, the effective water-cement ratio decreased, thus compensating for the negative effect that the recycled aggregate had on the strength. Figure 7 shows that the LSD interval increases as the percentage of replacement increases. This indicates that the negative qualities of recycled aggregates lead to the dispersion of results which ultimately would affect the characteristic compressive strength to be considered for the concrete.

When the results of the elastic modulus are compared, it is observed that the quality of recycled aggregates were the only influential factor. However, when the replacements were 20% or 50%, the effects were not significant. The effects were only important when the percentage of replacement was 100%. The variation of the elastic modulus was then significant with decreases of 26%.

The splitting tensile strength gave values and influences which were very varied, showing no evident trends, especially regarding the percentage of replacement. When this property is important, it should be checked.

The results are valid in the field of variation analyzed and it is necessary to expand the studies to aggregate of lower quality levels. It is also necessary to be able to verify the actual quality of available recycled aggregates on the market in order to validate the interest of this study.

Figure 2. Mean absorption and LSD intervals vs. type of aggregate.

Figure 3. Mean absorption and LSD intervals vs. % of replacement.
Figure 4. Occluded air mean and LSD intervals vs. type of aggregate.

Figure 5. Occluded air mean and LSD intervals vs. % of replacement.

Figure 6. Typified mean compressive strength and LSD interval vs. type of aggregate.
4. CONCLUSIONS

- The factors analyzed, such as declassified content, base concrete, target workability, sieve reference curves or replacement criteria are not influential, or their influence on the values of the property was not important.

- None of the factors analyzed showed a clear influence on the penetration of water under pressure.

- It is clear that the type of recycled aggregate and the percentage of replacement are the factors that clearly influence most of the properties, especially the absorption and the occluded air.

- Compressive strength is affected by the quality of the recycled aggregate, but if the total water-cement ratio is kept constant and the loss of workability due to the effect of the recycled aggregate is compensated for by the use of additives, the increase in the percentage of recycled aggregates used will not change the mean strength.

- The elastic modulus is affected by the percentage of replacement. If the percentage of replacement does not exceed 50%, the elastic modulus will only change slightly.

- The results obtained are valid in the field of variation analyzed. It is necessary to expand the studies to aggregates of lower quality levels. This study also raises the question of the need to be able to verify the actual quality of available recycled aggregates in order for the results of the study to be of practical use.
REFERENCES


