

Research Article

Effect of Cement Fineness on Recycled Aggregate Concrete Compressive Strength at Elevated Temperatures

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Abstract

Cement of different fineness CEMII42.5N and CEMII32.5N (EN 197-1) are used, to make concretes with aggregates that had been originated from recycled concrete standard cubic specimens of three different characteristic strengths. Specimen had been produced, during approximately one year, in order to control the production quality of a ready mixed concrete industry. As a consequence, recycled aggregates are of different ages and different compressive strength, such as those which could be taken from a recycling centre. Characteristic cubic strength of origin concrete was 15 or 20 or 25 MPa, and new concretes were made either with all their aggregates recycled or with virgin sand and recycled coarse aggregates. Compressive strength at 20°C and at temperatures up to 550°C was estimated, by both destructive and non destructive methods. Results were compared to those obtained from concretes made with virgin siliceous aggregates. Curves of compressive strength versus non-destructive tests before as well as after heating to high temperatures are given.

Keywords: Recycle Aggregate Concrete, Cement fineness, High temperatures, Residual strength, Non- destructive tests.

1. Introduction

Decrease of disposal landfills as well as the lack of natural resources and the tendency towards a viable management of construction and demolition waste led to recycling and re-use of it (M. Limbachiya *et al*, 2007), as a source of aggregates. Actually, it is broadly accepted today that recycling offers a financially viable and environmentally friendly solution (R. Dhir *et al*, 1999, C. Poon *et al*, 2002, K. Sagoe-Crentsil *et al*, 2001), and reviews have been published by many researchers [P. Nixon, 1978, T. Hansen, 1992, M. Behera *et al*, 2014, R.Silva *et al*, 2014]. These recycled aggregates have already been successfully used in new concretes [B. Topcu *et al*, 1995, M. Tavakoli *et al*, 1996] but despite environmental advantages from their use, most engineers hesitate to use a material for which there are not many guidance lines and specifications.

A big problem in recycling demolition debris is the variety of resultant aggregates, as well as heterogeneity and instability of their properties (A. Katz, 2003), mainly if their source is a recycling centre, which means that aggregates are collected from different origins (T. Hansen *et al*, 1983). The pollution of recycled materials constitutes one more problem, both during and after demolition (timber, plaster, plastics, glass etc), as well as before it (carbonation, chlorines, sulfates etc).

Apparently, these problems are decreased, when recycled aggregates originate from ready mixed concrete industries waste. This wastes originate from production control, washing of mixers at the end of every working day, returns because of delays, non-acceptance and from miscalculation of quantity. These wastes are alkaline, (PH \geq 11.5) and, if not properly managed, can influence the environment and human life polluting local underground water Tables and the ecosystem (B. Sealey *et al*, 2001). Exact data for the quantity of ready mixed concrete industry wastes don't exist, because, although industries are the same everywhere on the land, their production depends on local market differentiations. Moreover, due to competition among companies, the real levels of waste are hidden, particularly as there is no obligation for reporting [D. Fatta *et al*, 2003].

Very few investigations have evaluated the residual strength of concrete containing recycled materials at elevated temperatures (D. Cree *et al*, 2013). This work aims at investigating the properties of recycled aggregate concrete made with aggregate that had been produced from concrete standard cubic specimen, used for controlling the production quality of a ready mixed concrete industry. Although characteristic cubic strength of origin concrete is the same, the standard compressive strength is not equal, since they are produced from different concretes.

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It is examined, whether the compressive strength of recycled aggregate concretes is affected by the cement type (fineness) as well as the performance at high temperatures, either with destructive or nondestructive methods. Rebound hammer and pulse velocity are used, since they are two of the most common and relatively inexpensive methods (H. Qasrawi, 2000) that are easily applied in place. As it is known, rebound number and pulse velocity are affected by the aggregate type (S. Amasaki, 1991, A. Neville, 1995). Equations and curves of strength versus nondestructive values are given at different temperatures.

2. Experimental procedure

Two series of mixtures were prepared with the same cement content (330 kg/m^3) and the same water to cement ratio ($W/C=0.6$). Mixtures of the first series were made with CEM II42.5N, while mixtures of the

second series were made with CEM II32.5N. Both cements complied with EN 197-1 and are commercially available in Greece. All mixtures were made with aggregates that had been originated from concrete standard cubic specimen of characteristic strength $f_{ck}=15 \text{ MPa}$ (C12/15), $f_{ck}=20 \text{ MPa}$ (C16/20) and $f_{ck}=25 \text{ MPa}$ (C20/25), where $f_{ck} = f_{0.05}$. Specimen had been used, during approximately one year, for standard compressive tests for controlling the production quality of a ready mixed concrete industry. This means that recycled aggregates (RCA) were of different ages and different compressive strength, such as those which could be taken from a recycling centre.

For both series, six mixtures of recycled aggregate concrete (RAC) were prepared as well as one mixture with virgin aggregate, as reference normal concrete (code name N=Normal). The grading curve of all mixtures (Table 1) was similar and according to Greek Standards.

Table1 Aggregate grading curves of mixtures

| Mixture \ Sieves (mm) | 0,25 | 0,5 | 1,0 | 2,0 | 4,0 | 8,0 | 16,0 | 31,5 |
|-----------------------|-------------|------|------|------|------|------|------|------|
| | Passing (%) | | | | | | | |
| 100% C12/15 (R15) | 5.5 | 13.8 | 23.5 | 39.7 | 49.7 | 58.4 | 73.8 | 100 |
| 100% C16/20 (R20) | 6.0 | 14.0 | 22.8 | 39.3 | 49.3 | 57.9 | 74.2 | 100 |
| 100% C20/25 (R25) | 4.0 | 10.4 | 19.3 | 38.1 | 49.1 | 57.6 | 72.1 | 100 |
| 50% C12/15 (HR15) | 7.7 | 17.3 | 28.9 | 41.4 | 50.5 | 58.4 | 73.8 | 100 |
| 50% C16/20 (HR20) | 7.7 | 17.3 | 28.9 | 41.4 | 50.1 | 57.9 | 74.2 | 100 |
| 50% C20/25 (HR25) | 7.7 | 17.3 | 28.9 | 41.5 | 50.2 | 57.6 | 72.1 | 100 |
| Normal (N) | 7.7 | 17.6 | 29.2 | 42.2 | 51.7 | 57.4 | 61.9 | 100 |

Table 2 Physical properties of aggregate

| Type of Aggregate | Apparent density (kg/m^3) | | | Surface moisture (%) | | |
|-------------------|--------------------------------------|------------------|------------------|----------------------|------------------|------------------|
| | Sand | Coarse (4-16 mm) | Coarse (8-32 mm) | Sand | Coarse (4-16 mm) | Coarse (8-32 mm) |
| C12/15 | 2.20 | 2.38 | 2.44 | 1.060 | 1.030 | 1.010 |
| C16/20 | 2.20 | 2.43 | 2.44 | 1.063 | 1.024 | 1.015 |
| C20/25 | 2.20 | 2.42 | 2.47 | 1.069 | 1.026 | 1.020 |
| Virgin | 2.63 | 2.64 | 2.65 | 1.032 | 1.011 | 1.001 |

Table 3 Mix proportion of concretes

| Mixture | C | A | W | Virgin Aggregate (w/w %) | | | Recycled aggregate (w/w %) | | |
|---------|----------------------|--------|-----|--------------------------|------------------|------------------|----------------------------|------------------|------------------|
| | (kg/m ³) | | | Sand | Coarse (4-16 mm) | Coarse (8-32 mm) | Sand | Coarse (4-16 mm) | Coarse (8-32 mm) |
| R15 | 330 | 1541.1 | 198 | - | - | - | 50 | 9 | 41 |
| R20 | 330 | 1580.7 | 198 | - | - | - | 50 | 9 | 41 |
| R25 | 330 | 1551.0 | 198 | - | - | - | 50 | 9 | 41 |
| HR15 | 330 | 1683.0 | 198 | 50 | - | - | - | 9 | 41 |
| HR20 | 330 | 1729.2 | 198 | 50 | - | - | - | 9 | 41 |
| HR25 | 330 | 1696.2 | 198 | 50 | - | - | - | 9 | 41 |
| N | 330 | 1758.9 | 198 | 50 | 9 | 41 | - | - | - |

Three of the six mixtures of each series, one for every compressive strength class of original concrete, were made with all their aggregates recycled (code name R = Recycled) whereas the three remaining were made with virgin siliceous sand and recycled coarse aggregates (code name HR= Half Recycled). In Table 2 natural properties of all aggregates are given, while mix proportions are given in Table 3. It is noticed that recycled aggregates (the virgin ones also), had surface moisture, instead of the usual water absorption, because the day they were crushed and carried to the laboratory it was raining heavily.

To estimate the characteristic strength, 6 cubic specimen (15 cm) of each mixture were made, whereas the development in compressive strength at 20 °C and at high temperatures were determined on cubic (10 cm) specimen. All specimen were stored in an air-conditioned room at 20±2 °C and >95% relative humidity, up to 28 days. After that, they were kept exposed in a laboratory ambient.

Cubic specimen, before compression tests, were tested by means of the rebound hammer and pulse velocity. Average values of compressive strength and non destructive tests at each strength level (age) were treated as one data pair. Regression analysis was performed on the data pairs in order to obtain the best-fit estimation of the strength relationship.

At 12 months, the remaining specimens were heated in an oven, at 100°C, 300°C και 550°C, (2h at max temperature). After heating, specimens were kept exposed to cool in a laboratory ambient for 24 h, and then were tested for residual compressive strength (mean value of 3 cubes). Rebound number and pulse velocity were also estimated before and after heating.

3. Experimental results and discussion

3.1 Characteristic strength

Characteristic cubic strength ($f_{0.05}$) of all RAC (Table 4) is higher than that of concretes from which they originate and in most cases equal or even higher than that of normal concrete.

Table 4 Characteristic cubic strength of mixtures

| Mix | N | R | | | HR | | |
|----------------|--------------|----|----|----|----|----|----|
| | | 25 | 20 | 15 | 25 | 20 | 15 |
| f_{ck} (MPa) | CEM II 32.5N | | | | | | |
| | 20 | 25 | 30 | 25 | 25 | 20 | 25 |
| | CEM II 42.5N | | | | | | |
| | 30 | 30 | 30 | 25 | 37 | 30 | 25 |

The use of finer and stronger cement (CEMII42.5) either increases or doesn't affect the f_{ck} of mixtures. That means that f_{ck} is probably affected not only by the cement fineness but also by both the origin strength and the proportion of recycled aggregates. As origin concretes had been made up at different ages, recycled

aggregates didn't have the same compressive strength. Furthermore, because of different ages of origin concrete, the rate of hydration of old adhered cement was different.

3.2 Compressive strength at 20 °C

In Table 5, compressive strength of all mixtures at 20 °C is given.

Table 5 Compressive strength of mixtures at 20°C

| Compressive strength (MPa) | | | | | | | |
|----------------------------|--------------|------|------|------|------|------|------|
| Mixture | N | R25 | R20 | R15 | HR25 | HR20 | HR15 |
| Age | CEM II 42.5N | | | | | | |
| 7 | 24.6 | 26.6 | 23.8 | 26.7 | 26.4 | 30.7 | 26.5 |
| 28 | 29.4 | 30.9 | 28.8 | 30.2 | 29.5 | 33.9 | 30.6 |
| 90 | 33.4 | 35.2 | 35.6 | 32.3 | 34.6 | 37.4 | 34.3 |
| 180 | 39.0 | 38.0 | 38.4 | 32.7 | 37.8 | 39.8 | 35.6 |
| 365 | 46.6 | 39.6 | 39.6 | 32.9 | 38.4 | 41.6 | 36.0 |
| | CEM II 32.5N | | | | | | |
| 7 | 19.2 | 19.7 | 18.9 | 20.3 | 24.1 | 17.2 | 24.1 |
| 28 | 24.2 | 25.9 | 23.9 | 25.6 | 27.8 | 22.0 | 28.4 |
| 90 | 30.3 | 32.1 | 30.0 | 27.9 | 33.0 | 28.4 | 33.0 |
| 180 | 36.0 | 35.4 | 32.7 | 28.5 | 35.5 | 32.3 | 33.6 |
| 365 | 44.6 | 37.8 | 35.8 | 28.8 | 36.7 | 34.6 | 33.8 |

When CEMII42.5N is used, compressive strengths of RAC varies from 23.8 to 41.6, against 24.6-46.6 MPa of normal concrete. Mixtures made with CEMII32.5, present compressive strength from 17.2 to 37.8 MPa, against 19.2-44.6 MPa of normal concrete.

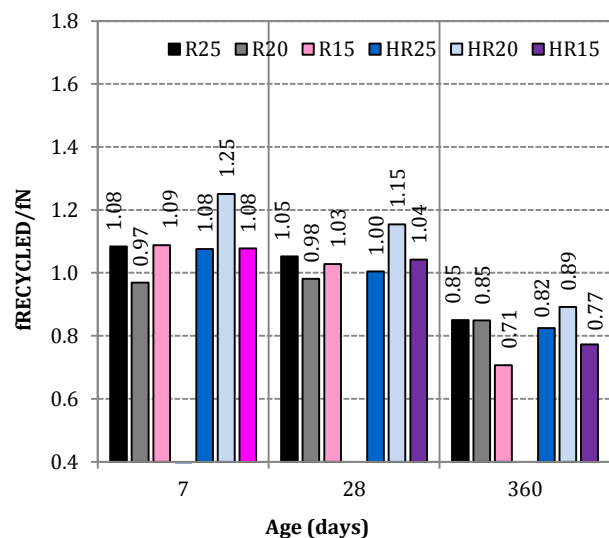


Figure 1 Ratio of compressive strength of RAC to that of Normal concrete. Mixtures made with CEM II 42.5N

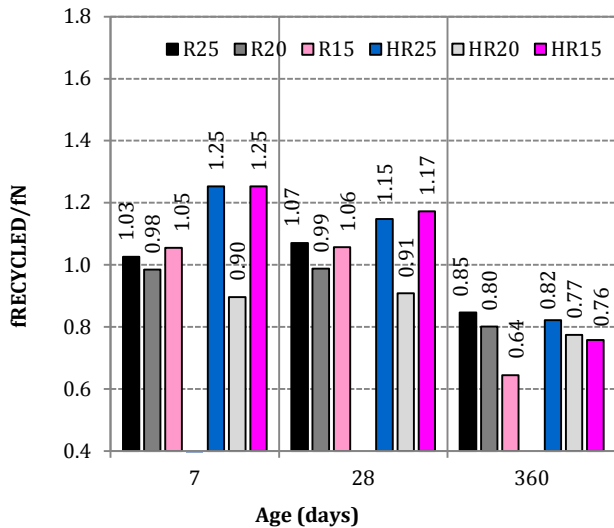


Figure 2 Ratio of compressive strength of RAC to that of Normal concrete. Mixtures made with CEM II32.5N

In comparison to normal concrete: Most of RAC made with CEMII42.5N (Figure 1), are stronger than normal concrete at 7 and 28 days. In more details, at 7 days, the compressive strength of 100% RAC (R mixtures) is 8-9% higher than that of normal concrete and respectively 3-5% at 28 days. In 50% RAC (HR mixtures), the corresponding increase is higher and ranges from 8 to 25% (at 7 days) and up to 15% (at 28 days). When CEMII32.5N is used, (Figure 2) R mixtures exhibit 3-7% higher strength than that of normal concrete up to 28 days, while this increase in HR mixtures is up to 25% at 7 days and 15-17% at 28 days.

However, one year later, normal concrete is 11-36% stronger than both R and HR mixtures. Therefore in comparison to normal concrete, almost all RAC exhibit higher strength, beyond the age of 90 days, irrespective the cement type or the rate of recycling. This is, probably, accomplished with the high water absorption capacity of the adhered mortar and also the rough texture of RCA, which leads to better bonding and interlocking properties between the mortar and RCA surface (N. Deshpande *et al*, 2014). This higher capacity lowers the effective w/c ratio in RAC, which in turn leads to increase the strength. However later age strength gain of RAC (from 90 to 365 days) is quite less than that of natural aggregate concrete.

The decrease of RCA percentage, (Figure 3), from 100% to 50%, in most mixtures, increases the compressive strengths from 5 to 29%, due to the lower strength of RCA, increased concrete porosity and weak interfacial bond between the aggregate and matrix. Wherever there was a reduction, it ranged only from 1% to 9%. Regarding to the effect of the cement type (Fig 4 and 5), mixtures made with the finer CEMII42.5 exhibit higher strengths than that with CEMII32.5, about 26-35%, 18-20% and 5-14% at 7, 28 and 365 days respectively. It is noticed that mixtures with 100% recycled aggregates (R) exhibit the same as the normal concrete increase of strength, whereas mixtures with 50% recycles aggregates (HR) are not

much affected by the cement type, with the exception of mixture HR20. This mixture, which had exhibited the highest characteristic strength among all mixtures, appears to be affected the most by the cement type, and when it is made with the finer CEMII42.5, it presents a strength increase of about 78%, 54% and 20% at 7, 28 and 365 days respectively. The reason for this is not clear. In any case, the trend in development in RAC compressive strength is similar to that in normal concrete. This means that mixtures made with a cement of greater fineness, present higher strength at an early stage, because of the rapid hydration of such cement. However, at later ages, the strength tends to be the same, no matter the fineness of the cement is.

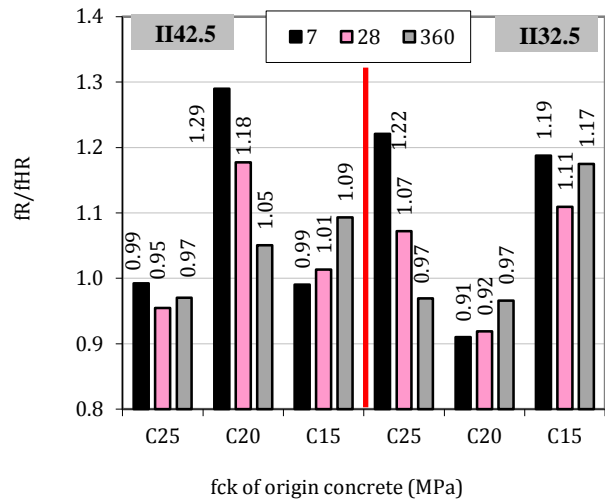


Figure 3 100% recycled (R) to 50% (HR) recycled aggregate concrete compressive strength ratio

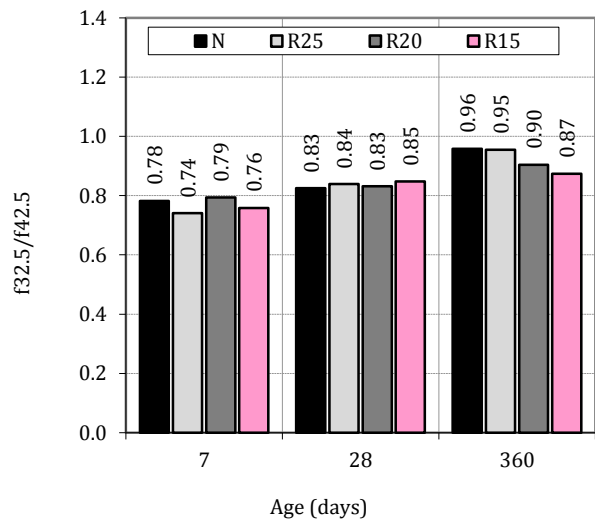


Figure 4 Compressive strength of R mixtures with CEMII 32.5N to that with CEMII 42.5N ratio, at 20°C

As for the influence of the origin concrete’s strength, the trend in one year compressive strength in RAC is, that the higher the original strength is, the higher the strength in RAC occurs. Compressive strength at ages beyond 1 year doesn’t appear to be affected by the origin strength by a definite way.

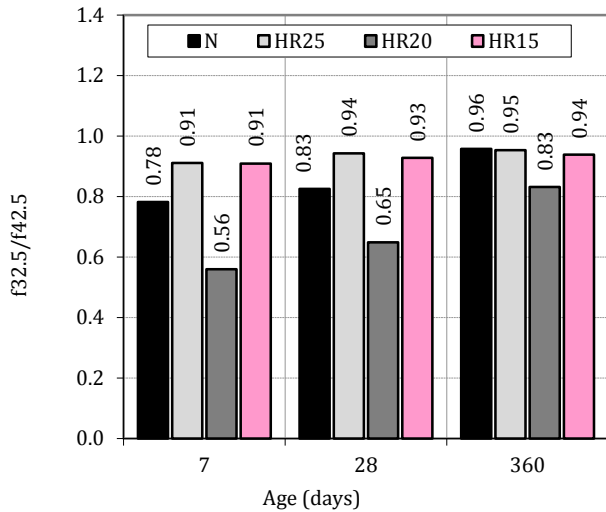


Figure 5 Compressive strength of HR mixtures with CEMII 32.5N to that with CEMII 42.5N ratio, at 20°C

3.4 Non destructive methods at 20 °C

The R number of mixtures was calculated as the mean of 10 measurements, taken from 4 opposite faces of each of 3 cubes, according to ASTM C 805, and is given in Table 6.

The position of the hammer was vertical to the surface of specimens, thus rebound numbers were smaller than those taken from a regular horizontal position.

Table 6 Rebound Number of mixtures at 20°C

| Rebound Number | | | | | | | |
|---------------------|------|------|------|------|------|------|------|
| Mixture | N | R25 | R20 | R15 | HR25 | HR20 | HR15 |
| CEM II 42.5N | | | | | | | |
| Age | | | | | | | |
| 7 | 12.0 | 12.7 | 12.1 | 10.9 | 14.5 | 12.7 | 12.0 |
| 28 | 13.8 | 14.5 | 14.9 | 14.3 | 15.6 | 15.0 | 14.8 |
| 90 | 15.0 | 16.2 | 19.2 | 16.4 | 17.3 | 17.9 | 17.2 |
| 180 | 16.7 | 17.1 | 20.8 | 16.9 | 18.2 | 19.6 | 18.1 |
| 365 | 18.9 | 17.7 | 21.9 | 17.4 | 18.6 | 21.0 | 18.6 |
| CEM II 32.5N | | | | | | | |
| Age | | | | | | | |
| 7 | 12.0 | 11.8 | 12.4 | 13.8 | 11.6 | 11.4 | 11.0 |
| 28 | 13.5 | 13.8 | 14.0 | 15.8 | 13.5 | 13.0 | 13.9 |
| 90 | 15.2 | 15.4 | 15.8 | 16.6 | 15.9 | 15.0 | 16.8 |
| 180 | 16.6 | 16.3 | 16.6 | 16.8 | 17.2 | 16.2 | 17.2 |
| 365 | 18.4 | 17.0 | 17.5 | 16.9 | 17.9 | 17.0 | 17.7 |

Rebound number in most RAC mixtures is higher than that in normal concrete, mostly if the cement is CEM II42.5. However, the differences aren't highly significant.

The type of cement does not actually affect the rebound number. Normal concrete with CEMII42.5 exhibits lower rebound number, while RAC mixtures exhibit higher values than those with CEMII32.5.

Reduction of recycling range increases the R number in most mixtures.

Table 7 Pulse Velocity (km/s) of mixtures at 20°C

| Pulse Velocity (km/sec) | | | | | | | |
|-------------------------|------|------|------|------|------|------|------|
| Mixture | N | R25 | R20 | R15 | HR25 | HR20 | HR15 |
| CEM II 42.5N | | | | | | | |
| Age | | | | | | | |
| 7 | 3.61 | 3.82 | 4.06 | 3.54 | 4.05 | 3.88 | 4.02 |
| 28 | 3.77 | 3.98 | 4.10 | 3.90 | 4.17 | 4.04 | 4.08 |
| 90 | 3.86 | 4.10 | 4.13 | 4.12 | 4.33 | 4.20 | 4.14 |
| 180 | 3.99 | 4.18 | 4.15 | 4.14 | 4.42 | 4.29 | 4.16 |
| 365 | 4.12 | 4.22 | 4.16 | 4.18 | 4.45 | 4.35 | 4.16 |
| CEM II 32.5N | | | | | | | |
| Age | | | | | | | |
| 7 | 3.66 | 3.92 | 4.05 | 3.82 | 3.78 | 3.68 | 3.67 |
| 28 | 3.85 | 4.01 | 4.09 | 4.07 | 4.02 | 3.95 | 4.01 |
| 90 | 4.02 | 4.09 | 4.12 | 4.16 | 4.30 | 4.20 | 4.30 |
| 180 | 4.15 | 4.12 | 4.13 | 4.18 | 4.42 | 4.34 | 4.36 |
| 365 | 4.32 | 4.15 | 4.13 | 4.19 | 4.48 | 4.43 | 4.37 |

In Table 7 pulse velocities of mixtures are given, as the mean of 6 values that is 2 measurements, taken from the two opposite faces of each of 3 cubes, according to ASTM C 597.

Pulse velocity in all RAC mixtures is higher than that in normal concrete, regardless of the cement type and age. However, the differences aren't highly significant and they range up to 8% at the age of 1 year.

The type of cement does not actually affects the pulse velocity, that is ranged from -8% to 10% at 7 days, while this range at one year is about -5 to 2%. Normal concrete with CEMII42.5 exhibits lower pulse velocity than that with CEMII32.5, at any age (1-5%). Reduction of recycling range increases the pulse velocity in all mixtures, at almost all ages.

3.5 Compressive strength at high temperatures

The residual compressive strength after heating at different temperatures T was expressed as a ratio f_T/f_{20} , where f_T is the strength after heating at T °C and f_{20} is the initial strength of concrete at 20 °C. The strength ratio f_T/f_{20} as a function of the specimens' temperature T is shown in Figure 6.

As shown in Figure 6, compared to normal concrete, at both 100 °C and 300 °C, all RAC are more resistant to fire, regardless of the cement type, the percentage replacement and the origin strength. Their residual strength, at 100°C is higher than normal concrete and this increase is 7-28% when CEMII 32.5 is used and 4-1% when CEMII42.5 is used. At 300°C, the corresponding increase is lower, 2-16% and up to 12% in mixtures with CEMII32.5 and CEMII42.5

respectively. At 550 °C, strength loss in all RAC appears to be similar, ranging from 57% to 66%. The respective loss in normal concrete is 60%, which is one of the lowest. Thus, almost all RAC are most resistant to fire compared to normal concrete.

Regarding to the origin strength, the trend in mixtures with 50% RCA (HR) is the higher the origin strength, the lower the residual strength after heating. There is no such a trend in mixtures with 100% RCA (R) and strength loss is in order of R20, R25 and R15, where R20 has the higher loss.

As regard to cement fineness, mixtures made with CEMII42.5 are stronger than those with CEMII32.5,

exhibiting lower strength loss, irrespective of the recycling rate or temperature (with the exception of HR20 and HR25 at 300°C which present higher loss). At 100° and 550 °C, the reduction of loss is 1-10% in all RAC and 8-14% in normal concrete. At 300 °C, the respective reduction in R mixtures is 20%, while in HR mixtures is 7-20%. In general terms, cement fineness affects the resistance of RAC against fire, mostly when the temperature is 300 °C, while normal concrete is more affected by it at both 300 and 550 °C.

Reduction of recycling rate from 100% (R) to 50% (HR) decreases the loss of strength, mostly when the cement is CEM32.5.

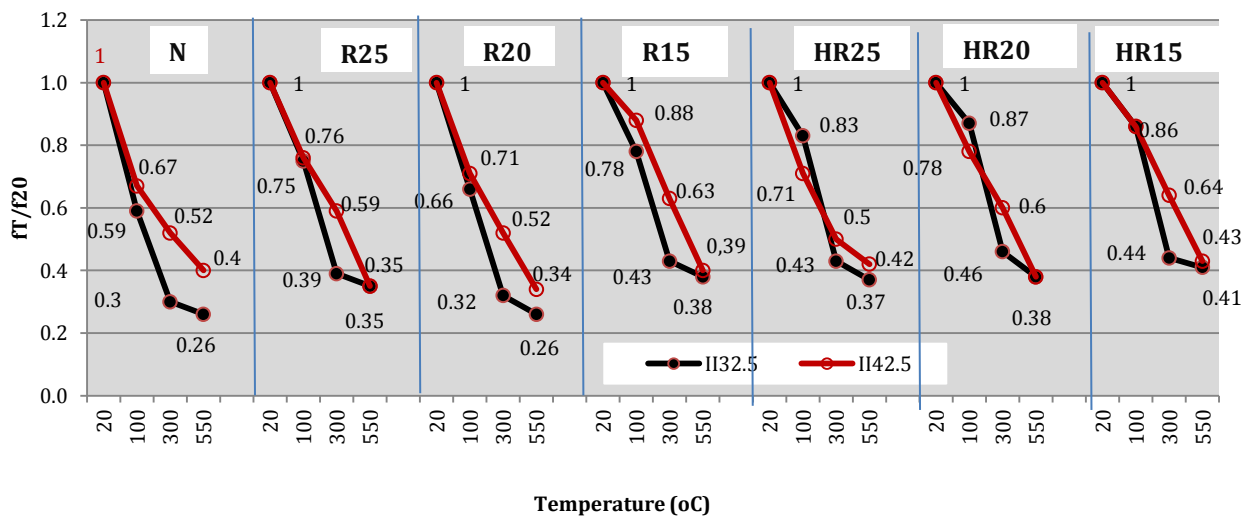


Figure 6 Residual strength of mixtures after heating at 100 °C, 300 °C and 550 °C

3.6 Non destructive methods at high temperatures

The residual rebound number after heating at different temperatures T was expressed as a ratio R_T/R_{20} , where R_T is the rebound number after heating at T °C and R_{20} is the initial rebound number of concrete at 20 °C. In Table 8, the ratio R_T/R_{20} versus the specimen temperature T is presented.

The residual rebound numbers in all mixtures are higher than those were obtained from destructive tests mainly when the cement is CEM32.5 or the temperature is 330 and 550°C. The rebound values are influenced mainly by the condition of the surface of concrete to depth not exceeding 3 cm approximately. Since increase of temperature causes drying and hardening of the surface layer, rebound measurements present a smaller reduction as compared to compressive strength loss.

The rebound numbers show that mixtures made with CEM42.5 exhibit greater strength loss, (or hardness), than that with CEMII32.5, normal concrete is more resistant than RAC and the redaction of recycling rate mainly increases the hardness loss in mixtures with CEM 32.5 and decreases it when the cement is CEM42.5.

Table 8 Residual rebound number and pulse velocity of mixtures after heating at 100 °C, 300 °C και 550 °C

| Mixture | 100 | 300 | 550 | 100 | 300 | 550 |
|--------------|--------------|------|------|--------------|------|------|
| | (°C) | | | | | |
| | R_T/R_{20} | | | V_T/V_{20} | | |
| | CEM II 42.5N | | | | | |
| N | 0,09 | 0,20 | 0,34 | 0,04 | 0,37 | 0,73 |
| R25 | 0,06 | 0,22 | 0,34 | 0,07 | 0,47 | 0,81 |
| R20 | 0,18 | 0,32 | 0,46 | 0,10 | 0,51 | 0,76 |
| R15 | 0,12 | 0,23 | 0,36 | 0,08 | 0,46 | 0,76 |
| HR25 | 0,21 | 0,27 | 0,37 | 0,15 | 0,42 | 0,78 |
| HR20 | 0,16 | 0,22 | 0,36 | 0,09 | 0,39 | 0,68 |
| HR15 | 0,11 | 0,17 | 0,30 | 0,15 | 0,42 | 0,78 |
| CEM II 32.5N | | | | | | |
| N | 0,03 | 0,13 | 0,32 | 0,06 | 0,40 | 0,62 |
| R25 | 0,04 | 0,12 | 0,23 | 0,02 | 0,46 | 0,65 |
| R20 | 0,10 | 0,19 | 0,19 | 0,03 | 0,43 | 0,71 |
| R15 | 0,10 | 0,17 | 0,22 | 0,03 | 0,44 | 0,70 |
| HR25 | 0,04 | 0,13 | 0,30 | 0,04 | 0,40 | 0,73 |
| HR20 | 0,08 | 0,15 | 0,22 | 0,07 | 0,39 | 0,64 |
| HR15 | 0,15 | 0,22 | 0,24 | 0,04 | 0,41 | 0,66 |

Table 9 Strength –Rebound number and Strength – Pulse velocity equations of mixtures

| Mixture | | f_T - R_T Equations | | | |
|-------------|------|--|---------------------------------|---------------------------------|---------------------------------|
| | | 20 °C | 100 °C | 300 °C | 550 °C |
| CEMII 32.5N | R15 | $f = 0.2253 \times R^{1.7163}$ | $f = 0.2113 \times R^{1.7163}$ | $f = 0.1328 \times R^{1.7163}$ | $f = 0.1313 \times R^{1.7163}$ |
| | R20 | $f = 0.1865 \times R^{1.8386}$ | $f = 0.1485 \times R^{1.8386}$ | $f = 0.0873 \times R^{1.8386}$ | $f = 0.0712 \times R^{1.8386}$ |
| | R25 | $f = 0.2317 \times R^{1.8002}$ | $f = 0.186 \times R^{1.8002}$ | $f = 0.1134 \times R^{1.8002}$ | $f = 0.1329 \times R^{1.8002}$ |
| | HR15 | $f = 4.1008 \times R^{0.7374}$ | $f = 3.9559 \times R^{0.7374}$ | $f = 2.1834 \times R^{0.7374}$ | $f = 2.0415 \times R^{0.7374}$ |
| | HR20 | $f = 0.24 \times R^{1.7579}$ | $f = 0.2449 \times R^{1.7579}$ | $f = 0.1458 \times R^{1.7579}$ | $f = 0.1419 \times R^{1.7579}$ |
| | HR25 | $f = 2.1558 \times R^{0.9842}$ | $f = 1.8676 \times R^{0.9842}$ | $f = 1.0568 \times R^{0.9842}$ | $f = 1.148 \times R^{0.9842}$ |
| | N | $f = 0.1476 \times R^{1.9588}$ | $f = 0.0938 \times R^{1.9588}$ | $f = 0.0577 \times R^{1.9588}$ | $f = 0.0805 \times R^{1.9588}$ |
| CEMII 42.5N | R15 | $f = 8.9277 \times R^{0.4585}$ | $f = 8.2816 \times R^{0.4585}$ | $f = 6.3424 \times R^{0.4585}$ | $f = 4.2825 \times R^{0.4585}$ |
| | R20 | $f = 2.761 \times R^{0.8649}$ | $f = 2.3219 \times R^{0.8649}$ | $f = 1.9915 \times R^{0.8649}$ | $f = 1.5915 \times R^{0.8649}$ |
| | R25 | $f = 1.3045 \times R^{1.1858}$ | $f = 1.0672 \times R^{1.1858}$ | $f = 1.0296 \times R^{1.1858}$ | $f = 0.7591 \times R^{1.1858}$ |
| | HR15 | $f = 4.4916 \times R^{0.7136}$ | $f = 4.1988 \times R^{0.7136}$ | $f = 3.2826 \times R^{0.7136}$ | $f = 2.472 \times R^{0.7136}$ |
| | HR20 | $f = 6.7478 \times R^{0.5958}$ | $f = 5.8401 \times R^{0.5958}$ | $f = 4.6982 \times R^{0.5958}$ | $f = 3.3233 \times R^{0.5958}$ |
| | HR25 | $f = 0.4189 \times R^{1.5494}$ | $f = 0.4305 \times R^{1.5494}$ | $f = 0.3414 \times R^{1.5494}$ | $f = 0.355 \times R^{1.5494}$ |
| | N | $f = 0.7001 \times R^{1.4281}$ | $f = 0.5332 \times R^{1.4281}$ | $f = 0.5023 \times R^{1.4281}$ | $f = 0.5034 \times R^{1.4281}$ |
| | | f_T - V_T EQUATIONS | | | |
| CEMII 32.5N | R15 | $f = 0.5152 \times e^{0.9606V}$ | $f = 0.4021 \times e^{0.9862V}$ | $f = 0.2203 \times e^{1.7083V}$ | $f = 0.197 \times e^{3.1689V}$ |
| | R20 | $f = 3E-14 \times e^{8.4263V}$ | $f = 2E-14 \times e^{8.6687V}$ | $f = 1E-14 \times e^{14.88V}$ | $f = 8E-15 \times e^{29.103V}$ |
| | R25 | $f = 0.0002 \times e^{2.9162V}$ | $f = 0.0001 \times e^{2.9616V}$ | $f = 8E-05 \times e^{5.3976V}$ | $f = 7E-05 \times e^{8.2572V}$ |
| | HR15 | $f = 4.0107 \times e^{0.4883V}$ | $f = 3.4293 \times e^{0.5067V}$ | $f = 1.7799 \times e^{0.8301V}$ | $f = 1.6256 \times e^{1.4414V}$ |
| | HR20 | $f = 0.5433 \times e^{0.9395V}$ | $f = 0.4749 \times e^{1.0049V}$ | $f = 0.2485 \times e^{1.5387V}$ | $f = 0.2086 \times e^{2.6251V}$ |
| | HR25 | $f = 2.449 \times e^{0.6045V}$ | $f = 2.0291 \times e^{0.6284V}$ | $f = 1.0424 \times e^{1.0029V}$ | $f = 0.9155 \times e^{2.1987V}$ |
| | N | $f = 0.1776 \times e^{1.2793V}$ | $f = 0.1056 \times e^{1.3566V}$ | $f = 0.0527 \times e^{2.1288V}$ | $f = 0.0462 \times e^{3.3924V}$ |
| CEMII 42.5N | R15 | $f = 8.419 \times e^{0.3268*V}$ | $f = 7.3758 \times e^{0.3558V}$ | $f = 5.305 \times e^{0.6041V}$ | $f = 3.298 \times e^{1.3455V}$ |
| | R20 | $f = 2E-08 \times e^{5.2216V}$ | $f = 1E-08 \times e^{5.7732V}$ | $f = 1E-08 \times e^{10.726V}$ | $f = 7E-09 \times e^{21.821V}$ |
| | R25 | $f = 0.5472 \times e^{1.0148V}$ | $f = 0.4159 \times e^{1.0902V}$ | $f = 0.3238 \times e^{1.9004V}$ | $f = 0.1935 \times e^{5.4728V}$ |
| | HR15 | $f = 0.0051 \times e^{2.1319V}$ | $f = 0.0044 \times e^{2.2841V}$ | $f = 0.0033 \times e^{3.3805V}$ | $f = 0.0022 \times e^{6.196V}$ |
| | HR20 | $f = 2.6422 \times e^{0.6321V}$ | $f = 2.0635 \times e^{0.691V}$ | $f = 1.5834 \times e^{1.0346V}$ | $f = 0.9984 \times e^{1.9848V}$ |
| | HR25 | $f = 0.5672 \times e^{0.9491V}$ | $f = 0.4029 \times e^{1.1173V}$ | $f = 0.2841 \times e^{1.6394V}$ | $f = 0.2369 \times e^{4.2963V}$ |
| | N | $f = 0.2463 \times e^{1.271V}$ | $f = 0.1649 \times e^{1.3258V}$ | $f = 0.1274 \times e^{2.0334V}$ | $f = 0.0978 \times e^{4.6856V}$ |

The residual pulse velocity after heating at different temperatures T was expressed as a ratio V_T/V₂₀, where V_T is the pulse velocity after heating at T °C and V₂₀ is the initial velocity of concrete at 20 °C. In Table 8, the ratio V_T/V₂₀ versus the specimen temperature T is presented.

Compared to residual compressive strength, the residual pulse velocity of mixtures is higher (greater density) at 100°C, and lower at 550 °C, while at 300 °C is lower when CEMII 42.5 is used and higher when CEM32.5 is used.

Normal concrete appears to be more resistant than RAC to thermal effect, and the reduction of recycling rate decreases the pulse velocity loss. RAC with CEMII32.5 are more resistant than those with CEMII42.5, while, up to 300°C, normal concrete is more resistant when CEMII42.5 is used.

As a resume, according to results obtained from non-destructive tests, mixtures made with the lower strength cement are more resistant against fire and the performance of normal concrete is greater than that of RAC. Thus, results obtained from direct and indirect methods are not in agreement.

It appears that the surfaces of RAC subjecting to the thermal effect are much softening and a net of internal cracking is generated, because of the deterioration of old, adhered, cement matrix. However, compressive strength is not correspondingly affected.

4. Strength versus nondestructive values

Based on results obtained of both compression and nondestructive tests at 20°C, and of the determined residual strength, rebound number and pulse velocity

after heating, relationships between compressive strength versus either rebound number or pulse velocity, at temperatures up to 550°C, are established. In Table 9 the equations of these relationships are given.

It is noticed that equations that relate the compressive strength with rebound number are a hyperbola one, while the equations relating strength with pulse velocity are an exponential one. All equations have a coefficient correlation $r^2 \geq 0.9985$.

Conclusions

- 1) The use of higher fineness cement (CEMII42.5) increases the f_{ck} , the compressive strength and the resistance to high temperature in all mixtures, irrespective the age, the strength of origin concrete, and the percentage range of recycled aggregate.
- 2) Reduction of recycling rate from 100% to 50%, increases both compressive strength and f_{ck} in all mixtures and reduces strength loss due to heating.
- 3) f_{ck} of all RAC is higher than origin concrete strength and higher or similar to normal.
- 4) At ages beyond one year, it is not clear how the origin strength affects the compressive strength in RAC. At one year, the higher the origin strength is, the higher the strength in most RAC results.
- 5) All RAC present higher than normal concrete compressive strength, beyond the age of 90 days, and lower thereafter, regardless of the cement type.
- 6) Normal concrete is less resistance to fire at 100 and 300°C. At 550 °C the strength loss of normal concrete is the highest when CEMII32.5N is used and slightly lower when CEM II42.5N.EM is used.
- 7) The residual strength after fire, regarding to the origin strength, does not exhibit a clear trend.
- 8) Explosive spalling was not observed for RCA or normal concretes
- 9) Equations of strength versus non destructive values are given

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