Mechanical Performance of Structural Concrete with the Incorporation of Coarse Recycled Concrete and Ceramic Aggregates

M. Gomes[1]**, J. de Brito**[2] **and M. Bravo**[3]

DECivil-IST, Technical University of Lisbon, Av. Rovisco Pais, 1049-001, Lisbon, Portugal

ABSTRACT: The paper presents the results of an experimental programme to evaluate the viability of concrete made when various ratios of coarse natural aggregates (CNA) are replaced with coarse recycled concrete aggregates (CRCA), coarse recycled ceramic masonry and mortar aggregates (CRMMA), or both. Results show that the incorporation of CRCA and of CRCA and CRMMA simultaneously has no effect on compressive strength. However this property decreases when only CRMMA is incorporated. A reduction of 23.6% in compressive strength was obtained when 50% of CRMMA was used. Splitting tensile strength is unaffected by the incorporation of CRCA, but it is affected by the incorporation of CRMMA. The mixes with 50% of CRMMA showed a reduction of 20.1% in tensile strength. Every recycled aggregates concrete (RAC) type suffered a linear decrease of modulus of elasticity as the replacement ratio of CNA by coarse recycled aggregates (CRA) increased. The use of 100% of CRCA caused a decrease in modulus of elasticity of 30%. In the mixes with 50% of CRMMA that decrease was 22.2%. Finally, shrinkage was significantly affected by the incorporation of CRA, though the degree of shrinkage varied according to their nature and incorporation ratio. For replacement ratios between 50% and 100%, the difference between RC and the mixes with CRCA remained constant, inside a 30% increase range.

---

[1] MSc in Civil Engineering, IST - Technical University of Lisbon, Av. Rovisco Pais, 1049-001, Lisbon, Portugal, e-mail: marco.gomes@civil.ist.utl.pt

[2] Full Professor, Department of Civil Engineering and Architecture, IST - Technical University of Lisbon, Av. Rovisco Pais, 1049-001, Lisbon, Portugal, e-mail: jb@civil.ist.utl.pt, Phone: (351) 218419709; Fax: (351) 21 8497650), Corresponding author

[3] MSc in Civil Engineering, IST - Technical University of Lisbon, Av. Rovisco Pais, 1049-001, Lisbon, Portugal, e-mail: miguelnbravo@gmail.com

Subject headings: concrete, recycled concrete aggregates, recycled masonry and mortar aggregates.

INTRODUCTION

The construction industry both drives the progress of Society and is a major contributor to serious environmental impacts. One of the most visible aspects of these impacts is construction and demolition waste (CDW), which represents from 20% to 30% (including soil) of all the solid waste produced each year.

Table 1 shows the average figures for CDW production in various European countries. The information was taken from a paper from the European Union in 2003 (Muthmann, 2006), and the average annual growth rates determined from Eurostat Environmental Statistics and an estimation of *per capita* production have been added. Due to some inconsistencies, these results should be viewed with caution especially where they differ most from a previous estimate, put together in the so-called Symonds report (Symonds, 1999).

Unfortunately, most of these waste products are not reintroduced into the construction process as aggregates for concrete production, one of the few options not considered *downcycling*, i.e. when the materials are used for a less demanding function than the original one, and therefore very little is gained from their intrinsic value (in terms of cost or potential properties). One of the main reasons for this trend is the absence or conservative stance of regulations that would allow the use of recycled aggregates in concrete production (Gonçalves and de Brito, 2010).

This paper presents part of the results of an experimental programme developed at Instituto Superior Técnico (IST) where the technical viability of replacing natural coarse aggregates with coarse aggregates recycled from concrete and rendered brick partition walls was studied to supplement the data on durability performance already published (Gomes and de Brito, 2009). The mechanical performance of the concrete mixes tested was evaluated through the following properties: compressive strength, splitting tensile strength, modulus of elasticity, and shrinkage.

On the one hand, this research allows evaluating the influence of the use of coarse recycled concrete aggregates and coarse recycled ceramic masonry and mortar aggregates in concrete production. On the other hand, taking into account that all mixes were made in the same way, it also allows comparing the results for each of these types of waste, the most important ones in CDW. The research also analyses the simultaneous use of these aggregates' types. This evaluation is important because it simulates, in a controlled way in laboratory conditions, what would occur in concrete production with CDW from an actual recycling plant. This eliminates any factor that could disturb the concrete properties, besides the ones under consideration (incorporation ratio of coarse recycled concrete aggregates and/or ratio of coarse recycled ceramic masonry and mortar aggregates).

LITERATURE REVIEW

The selected works described below report experimental research on the mechanical properties of concrete made with recycled aggregates similar to those used in the present work. Most of the work was carried out at IST, Technical University of Lisbon, Portugal.

Compressive strength

Santos et al. (2004) tested beams made of a reference concrete (RC), with w/c of 0.55 and slump of 62 mm, and two recycled aggregates concrete (RAC) mixes, both without coarse natural aggregates (CNA) and with coarse recycled aggregates (CRA) of crushed concrete from the demolition of a stadium, but with different water/cement ratios (0.55 and 0.63) and slump values (18 mm and 62 mm), and determined their compressive strength: 38.4 MPa, 38.4 MPa and 32.7 MPa, respectively. The authors concluded that the use of CRA instead of CNA may lower concrete's compressive strength and that this property can be significantly affected by the w/c ratio. Maintaining the water/cement ratio in the first RAC, at the cost of reducing the workability, offset the expected reduction of compressive strength in the second RAC by reducing the amount of free water. The same authors (Santos et al., 2002) tested an RC without CRA and two RACs, both without CNA and with CRA from concrete mixes with different water/cement ratios, keeping the slump value constant at 85 ± 10 mm. They concluded that compressive strength (at 7 and 28 days) was lower because of the replacement of CNA with CRA (due to the mortar still adhering to the original stone particles after concrete is crushed). This property did not seem to be significantly affected by the original source concrete of the CRA. The same authors tested one RC and two RACs, with 50% and 100% replacement of CNA with CRA of crushed concrete, and concluded that, even though the compressive strength is similar for the RC and the RAC for small replacement ratios (confirming the findings of Limbachyia et al. (2000) for high-performance concrete up to a 30% ratio), the difference tends to increase roughly proportionally to the replacement ratio.

De Brito et al. (2005) determined the compressive strength of one RC and three RACs in which the CNAs were replaced by 1/3, 2/3 and 3/3 of coarse ceramic brick aggregate, with the same slump value and effective w/c ratio as the RC. The grading curve of the CNA and coarse ceramic brick aggregate was also exactly the same. A clear descending trend with a high correlation ratio ($R^2 = 0.927$) was obtained for the compressive strength/replacement ratio relationship. The compressive strength of the RAC with only ceramic coarse aggregates was 45% lower than that of the RC with limestone coarse aggregates only.

Evangelista and de Brito (2007) produced one RC and five RACs in which 10%, 20%, 30%, 50% and 100% of fine natural aggregates (FNA) were replaced with fine recycled concrete aggregates (FRCA), with the same slump value and effective water/cement ratio as the RC. Again, the grading curves of the FNA (water absorption of 1%) and FRCA (water absorption of 13%) were exactly the same. Contrary to the previous results and to existing preconceptions, the variation in compressive strength for the various mixes was insignificant and no visible trend due to the FNA replacement by FRCA was found. Several authors (Katz, 2003; Poon et al., 2004; Barra and Vásquez, 1996) have offered possible explanations, the most relevant of which is that fine recycled aggregates have high amounts of cement (both hydrated and non-hydrated), that can reach as much as 25% of their weight, and this increases the total amount of cement in the mix.

Matias et al. (2013a) compared an RC with two RACs with the same slump value where the CNA had been totally replaced by CRA, with exactly the same grading curve, and two different superplasticizers had been used to compensate for the CRA's drawbacks (in particular its much greater water absorption). The results for compressive strength were similar in the various mixes and no trend was detected in terms of replacement ratio (corroborating the results of the earlier research but with coarse instead of fine aggregates, even though here the main reason is probably the use of superplasticizers) or the effect of the type of superplasticizers.

Tensile strength

In the same research program reported above, de Brito et al. (2005) determined the flexural tensile strength of three small slabs (5 x 40 x 60 cm) made with each of the concrete mixes. Like the compressive strength, this property also decreased with the higher percentages of replacement of limestone aggregates with ceramic aggregates. Again, these results indicate a linear relationship between the two factors. In addition, the relative reduction in flexural strength when all coarse primary aggregates are replaced is only 26%, much less than that for compressive strength, a trend far from being matched in other experimental works.

Evangelista and de Brito (2007), in the same experimental research quoted above, but testing only two RACs with 30% and 100% replacement of FNA with FRA (fine recycled aggregates), obtained the following results for splitting tensile strength: the RAC with

30% FRA had a performance 5% worse than the RC's, and that with 100% FRA was 30% worse. The authors suggest that this discrepancy with the compressive strength results is because tensile strength does not particularly benefit from the additional cement that is incorporated along with the FNA, and therefore the more porous structure of the recycled aggregates explains the decrease of the tensile strength with the incorporation ratio increase.

Matias et al. (2013a) determined the splitting tensile strength of the various mixes an obtained the following results (average of 3 specimens per mix): 4.41 MPa for the RAC and reductions of 5% and 16% for the RAC with the different superplasticizers. These results are somewhat inconclusive but it can be said that they show a downward trend of tensile strength as a function of the replacement ratio that depends on how effective the superplasticizer is at offsetting the drawbacks of the recycled aggregates compared with the natural aggregates.

Olorunsogo (1999) tested the 28-day flexural tensile strength of concrete with CRA consisting of more than 90% of concrete and mortar, with replacement ratios of 30%, 50%, 70% and 100%. The respective values obtained were 7.8 MPa, 7.3 MPa, 6.3 MPa and 7.8 MPa, and 7.8 MPa for the RC. Based on these results the author concluded that no trend could be detected in terms of flexural tensile strength as a function of the replacement ratio and that the values for the various RACs were similar to that for the RC.

The studies referred above demonstrate that the concrete tensile strength remains similar when coarse recycled concrete aggregates (CRCA) are used. On the contrary, the use of ceramic aggregates resulted in a decrease of this property

Modulus of elasticity

Santos et al. (2002) compared the 32-day modulus of elasticity of one RC with that of two RACs with coarse recycled concrete aggregates (CRCA). The authors obtained reductions of 22% and 33% for total replacement of the CNA. This decrease is greater than the one for compressive strength, around 20% for both RACs. This difference is linked to the different original concrete mixes' source of the CRCA and demonstrates the influence of the quality of the original concrete on the deformability of the structural elements made with RAC.

Kou et al. (2004) studied the modulus of elasticity in concrete mixes with CRA from CDW in percentages of 0, 20%, 50% and 100% of the total weight of coarse aggregates. The authors determined the 28-day and 90-day modulus of elasticity and found reductions of 40% and 28%, respectively, for total replacement of the CNA.

Oliveira et al. (2004) evaluated the influence on the modulus of elasticity of the 10%, 20%, 30%, 40% and 100% replacement of CNA with CRA. The CRA came from CDW mostly made of concrete waste. The authors found that total replacement of CNA led to an 18% reduction of this property.

Evangelista and de Brito (2007) found a maximum decrease of the modulus of elasticity of 20% when all FNA were replaced by FRA from crushed concrete. They also detected a linear relationship between the modulus of elasticity and CRCA incorporation ratio.

All studies concur on a decrease of the modulus of elasticity when recycled concrete aggregates are used. This trend is valid both for fine and coarse aggregates.

Shrinkage

Santos et al. (2002) evaluated the shrinkage of one RC and two RACs made with CRCA. They found an increase of 45% and 84% in the 28-day shrinkage of RAC with 100% replacement of CNA, according to the original source concrete of the CRCA, proving that it is a conditioning factor in the long-term behaviour of structural elements made with RAC. In both cases the increase was due to the lower bulk density of the CRCA compared to that of the CNA and to the increase of the water/cement ratio from 0.56 (RC) to 0.65 (both RAC).

De Pauw et al. (1998) produced one RC and three RACs (one with CRCA and two with ceramic CRA). Shrinkage was measured at 460 days. The authors concluded that the shrinkage after 28-days may differ in relative terms from that after 1 year. This is because the RC has faster initial shrinkage but it slows down significantly after 2 to 3 months. This trend was also detected by Matias et al. (2013a). De Pauw et al. (1998) also found that the increase in cement content reduces shrinkage less efficiently than the use of superplasticizers. Finally they observed that the CRA's size distribution and mineral source influence the shrinkage evolution.

Evangelista and de Brito (2007) found a significant increase in the shrinkage of RAC mixes with 50% and 100% ceramic FRA. However, no noticeable change in this property occurred for aggregate replacement ratios below 30%.

Matias et al. (2013a) tested RAC with full replacement of CNA with CRCA and different plasticizers. Based on the results they concluded that the type of plasticizer has a significant influence on concrete shrinkage. The RAC with the lower performance plasticizer had an increase of 45% compared to the RC, while shrinkage of the RAC with the higher performance plasticizer only increased 22.5%.

These studies in consensual in that the shrinkage of RAC (concrete or ceramic) is higher that of the RC. Various studies conclude that this trend is inverted in the first days.

EXPERIMENTAL PROGRAM

Materials used

Calcareous natural aggregates (NA) were used throughout the work. Coarse aggregates were considered as ground and fine aggregates as rolled.

Concrete recycled aggregates were obtained in laboratory by crushing prismatic specimens of ready-mixed concrete. This original concrete belonged to compression reference class C 30/37 and had a maximum aggregate size of 25 mm. The specimens were crushed in a jaw-crusher at 35 days. The ceramic masonry plus mortar aggregates used in this work came from the demolition of some 6 month-old walls on a worksite approximately. They were built of ceramic hollow bricks and two mortar layers using cement type CEM II 32.5R and a clayish sand. These materials were used to replicate artificial CDW (concrete, ceramics and mortar) while controlling their origin, homogeneity and properties.

Cement type CEM II A-L 42.5 R and tap water were used to make the concrete mixes. No admixture was used.

Concrete mixes' composition

Based on standard EN 206-1 (2000) a reference concrete (RC) with a compressive strength class of C 30/37 and workability within the slump range 80±15 mm was produced. The experimental programme involved two stages with the intention of evaluating different factors. In the first stage the main objective was to determine the mixes with coarse recycled aggregates (CRA) whose performance would not differ from the RC's performance, in a series of pre-established properties, beyond given limits. In the second stage the aim was to evaluate as thoroughly as possible the concrete mixes with maximum CRA incorporation whose performance still complied with the limits defined in the first stage.

The following compositions with different replacement ratios of coarse natural aggregates (CNA) by CRA were tested: C12.5C (mix with 12.5% replacement, in weight of coarse aggregates, of CNA by CRA from crushed concrete - CRCA), C25C, C50C, C100C, C6.25CM (mix with 6.25% replacement, in weight of coarse aggregates, of CNA by ceramic masonry plus mortar CRA - CRMMA), C12.5CM, C25CM, C50CM, C6.25CM12.5C (mix with 6.25% replacement, in weight of coarse aggregates, of CNA by CRMMA and 12.5% replacement, in weight of coarse aggregates, of CNA by CRCA), C12.5CM25C and C25CM50C (Figure 1).

The fine aggregates fraction (natural sand) was the same for all the mixes. The coarse fraction had the same particles size distribution for all aggregate's types, i.e. an artificial curve determined using the Faury method that forced the sieving of every coarse aggregate used. This prevented this factor from interfering with the results.

The effective water/cement ratio was also constant for all the mixes. This was achieved by pre-saturating all the recycled aggregates (RA), because of their greater water absorption capacity compared with that of the NA. The amount of extra water required was determined using a method that allows tracking the progression of the water within each type of aggregate (Ferreira et al., 2011).

Tests

The aggregates were characterized using the following tests:

- Size distribution- EN 933-1 (1997) and EN 933-2 (1995);
- Bulk density and water absorption - EN 1097-6 (2000);
- Loose bulk density - EN 1097-3 (1998);
- Water absorption over time (only for CRA);
- Volume index - LNEC E223 (1968) (only for coarse aggregates);
- Los Angeles wear - EN 1097-2 (1998).

The tests performed on fresh concrete were as follows:

- Slump test (Abrams cone) - EN 12350-2 (2009);
- Density - EN 12350-6 (2009).

The following tests were performed on hardened concrete:

- Compressive strength at 7, 28 and 56 days - EN 12390-3 (2003);
- Splitting tensile strength - EN 12390-6 (2009);
- Modulus of elasticity at 28 days - LNEC E397 (1993);
- Shrinkage - LNEC E398 (1993).

RESULTS AND DISCUSSION

Properties of aggregates

Table 2 shows the results of the tests on aggregates. The particle bulk density of CRA is lower than that of CNA. This is basically because the cement paste that adheres to the latter (concrete paste in the CRCA and coating mortar in the CRMMA) has a lower density than the stone aggregate. In the case of the CRMMA this situation is aggravated by the lower particle bulk density of ceramics and current renders compared with the stone used as coarse aggregate in concrete.

CRA revealed much higher water absorption than NA. CRCA had a value of 8.49% and CRMMA 16.34%, which is explained by the higher absorption capacity of the hardened paste adhered to the natural aggregates as well as by the rougher surface of the CRA. As for the crushed ceramic aggregates, their high porosity is well known and their elongated shape further enhances their water absorption capacity.

The Los Angeles wear test indicated that there is a higher wear of the CRA than of the CNA, explained by a lower binding capacity of the cement paste adhered to the natural aggregates and a lower intrinsic strength of the ceramic part of the CRMMA. The wear increase over the CNA values was 33% for the CRCA and 130% for the CRMMA, which clearly confirms that the latter is the least able to be used in structural concrete (Table 2). As observed for the particle bulk density - and for exactly the same reasons - the loose bulk density of CRA is lower than that of the CNA.

The volume index test was performed to analyse the shape of the particles and thus understand its influence on concrete workability. The results showed that the CNA volume index decreases with the particles size, just as it does for the CRA. Within the CRA, CRMMA have the higher volume index due to their rougher surface and elongated shape.

Fresh concrete properties

Workability

Workability is one of the properties most affected in RAC due to the higher water absorption of the RA. In fact RAs tend to absorb part of the mix's free water, thus reducing its plasticity. In order to tackle this effect an experimental method was developed (Gomes and de Brito, 2009) to allow understanding of how the CRAs absorb water over time. Thus the parcel of water absorbed by the CRA during mixing was determined and it was initially added to the mix to guarantee the cement's hydration. This compensation results in the need to determine two water/binder ratios, the apparent and the effective one.

Results show that the workability of the various mixes remained within the pre-defined slump range of 80 ± 15 mm, measured with the Abrams cone (Table 3). This situation is considered essential for a correct direct comparison of all concrete properties.

Density

The fresh concrete density reflects the bulk density of each of its components and their degree of compaction. Therefore, and according to the results, the difference in density between the fresh mixes tends to increase as the difference in bulk density of the aggregates and the CNA/CRA replacement ratio also increases (Table 4). It is concluded that there is a linear relationship between fresh concrete density and the CNA/CRA replacement ratio.

Hardened concrete properties

Compressive strength

The compressive strength tests were performed in two stages. First, 6 specimens per mix type were tested at 28 days and then 3 specimens were tested at 7 days, 5 at 28 days and 2 at 56 days. Results from the first stage are presented in Table 5.

To better perceive the results strength in relation to CRA incorporation, ratio curves were plotted (Figures 2 to 4). Figure 2 shows there is no significant variation in compressive strength between the various mixes when the incorporation ratio of CRCA changes. The same had already been found by Evangelista and de Brito (2007) for fine recycled concrete aggregates.

However, Figure 3 demonstrates that the compressive strength of the mixes with CRMMA is strongly affected by their incorporation ratio.

When CRA totally replaces CNA (solely ceramics made from crushed hollow bricks) de Brito et al. (2005) obtained mechanical strength losses of 45% relative to the RC. This figure is similar to the theoretical value obtained using the linear regression line shown in Figure 3. De Brito et al. also found a linear relationship between compressive strength and the CNA/CRA replacement ratio, which confirms the results of our study.

The mixes in which CRCA and CRMMA were incorporated simultaneously (Figure 4) yielded very interesting results. The compressive strength of these specimens remained practically constant until the maximum replacement ratio of 75% RA, for mix C25CM50C.

In the second stage of the experimental campaign, besides the RC some RAC mixes were studied. These were the mixes that had resulted in first stage losses lower than 15% of the average compressive ultimate stress and with a feasible CRA incorporation rate. The specimens were tested until failure at different ages with the objective of understanding their behaviour over time and comparing it with that of the RC.

The results of this second stage are summarized in Tables 6 to 8. Comparing the results of the first and second stages clearly shows that there was a general and approximately constant small decrease in corresponding mixes. This indicates there was an involuntary change in the mixes’ composition that was the same for all the second stage mixes. This is linked to a slight improvement in workability (within the pre-defined range) and shows how important it is to effectively control this property when undertaking comparative studies.

Figure 5 shows how compressive strength develops for the various mixes tested in the second stage. It is concluded that the strength of RAC tends to develop favourably after 56 days, which contrasts with the strength stagnation exhibited by the RC after 28 days of curing. This indicates that the hydration of cement within the RAC occurs more slowly than for the RC.

Splitting tensile strength

Results from the three specimens per concrete mix tested are found in Table 9. They show that the splitting tensile strength of concrete is affected by the nature of the aggregate surface (which relates to its adhesivity to the cement paste) and its ultimate tensile strength. These factors explain the lower tensile strength of the RAC with CRMMA compared with that of the RAC with CRCA, regardless of the incorporation ratio of CRA.

Of the mixes with a mixture of CRA the one with 12.5% CRMMA and 25% CRCA showed a loss of tensile strength of 17.9% compared with the RC.

The results obtained demonstrate that the tensile strength is not affected by the replacement of CNA with CRCA for mixes with the same cement content and effective water/cement ratio. A slight positive effect was even found, caused by the higher surface roughness of the CRCA.

The splitting tensile strength of the mixes with CRMMA shows a linear decreasing trend as the incorporation ratio increases (Figure 6). De Brito et al. (2005) had similar results when they performed flexural tensile tests on slabs (180 x 400 x 40 mm) made with RAC containing ceramic aggregates.

Modulus of elasticity

Three cylindrical specimens with a diameter of 150 mm and a height of 300 mm were produced per concrete mix. They were tested in three cycles of loading until the difference between the averages of the strain variations of two consecutive cycles was less than 10×10^{-6}. The results obtained per specimen are listed in Table 10.

The modulus of elasticity of the RAC was lower than that of the RC because of the lower bulk density of the CRA. Thus the incorporation of CRA decreases the structural stiffness of concrete because their strength and bulk density are lower than those of the CNA. This trend is sharper when CRMMA are used.

For an incorporation of 50% CRCA in weight there is a 10.2% reduction of the modulus of elasticity. This value corroborates the potential to use RAC in current structural applications. Figure 7 clearly shows that the modulus of elasticity of the RAC with CRCA changes linearly with the CNA replacement ratio, a similar conclusion to that reached by Evangelista and de Brito (2007) for fine recycled concrete aggregates.

The maximum incorporation of CRMMA tested (25%) led to a 15.8% fall in the modulus of elasticity compared with the RC. This indicates that a higher incorporation ratio should not be used if CRMMA were to be used in structural applications (the limit of loss of the modulus of elasticity of RAC imposed in the reference literature is 20% with respect to an RC). Figure 8 shows that the variation of the modulus of elasticity as a function of the CNA/CRMMA is approximately linear (R^2=0.9448).

Of the mixes with a mixture of CRA the one with 12.5% CRMMA and 25% CRCA showed a loss of modulus of elasticity of 16.2% compared with the RC. This is very close to the relative loss of tensile strength of the same mix (17.9%).

Shrinkage

Two specimens per concrete mix were tested (in both the first and second stages of the experimental programme) by being placed in a dry chamber under controlled temperature and humidity. There were some technical problems that led to different relative humidity levels in the two stages (around 55% in the first one and 70% in the second). This precludes direct comparisons between the absolute values from the mixes common to the two stages. Therefore the analysis was made in relative terms by dividing the results of each

RAC mix by the corresponding values of the RC. Hyperbolic regression curves were used to smooth the individual measurements, in accordance with *Comité Euro-International du Béton* - Model Code 90 (1990). These curves are shown in Figures 9 to 11.

It was found that concrete shrinkage was similar to that of the RC up to a 25% limit of incorporation of CRCA. But absolute values were considerably higher than for the RC for the C50C and C100C mixes. Santos et al. (2002) reached the same conclusion when analysing the 28-day shrinkage of mixes with 100% of CRCA.

It was also found that for incorporation ratios of CRMMA of 12.5% or less the RAC shrinkage was lower than that of the RC. For ratios between 12.5% and 50% shrinkage was still below that of RC in the initial ages. However, the situation was reversed after 35 days. This can be explained by the release of free water within the CRMCA pores into the cement paste, thus attenuating autogenous shrinkage, whose relative importance in overall early-age shrinkage tends to be quite high. This also explains the reversal of the trend after 35 days. De Pauw et al. (1998) and Matias et al. (2013b) also found that RC has an initial shrinkage higher than that of concrete with ceramic aggregates and that this trend reversed later on.

Within the mixes containing both CRCA and CRMMA the C6.25CM12.5C mix shows a shrinkage performance similar to that of the RC after 100 days. On the other hand the C12.5CM25C and C25CM50C mixes have a similar behaviour, though it is slightly better in the first. Both mixes had shrinkage levels around 40% higher than the RC.

Figure 12 shows the relative shrinkage coefficients of the RAC mixes tested in the second stage of the experimental programme. It is clear that the RAC's shrinkage after 30 days can be estimated based on the RC's shrinkage. For that one must multiply the RC's shrinkage by the approximately constant value of the last stretch of each mix's curve.

CONCLUSIONS

The mechanical performance of coarse RAC was analysed in this work. In this study concrete was produced with the two main CDW, artificially made in laboratory. These mixes intend to simulate very approximately the results that would be obtained using recycled aggregates from CDW of a real recycling plant.

It is concluded that, both for the incorporation of coarse recycled concrete aggregates (CRCA) up to 100% and the simultaneous use of CRCA and coarse recycled ceramic masonry and mortar aggregates (CRMMA) up to a joint value of 75% in coarse RAC production, there is no significant difference in compressive strength. Evangelista and de Brito (2007) reached the same conclusion with fine recycled concrete aggregates. However the incorporation of CRMMA alone leads to a reduction in compressive strength right from the start of the replacement. De Brito et al. (2005) also found a 45% reduction of concrete compressive strength with 100% coarse ceramic aggregates relative to RC.

Splitting tensile strength was unaffected by the incorporation of CRCA in the mix. The results were similar to those for compressive strength. For the mixes with CRMMA a linear trend of loss of ultimate tensile stress was found to be related to the ratio of CRMMA in the mix. De Brito et al. (2005) had similar results when they performed flexural tensile tests on slabs made with RAC containing ceramic aggregates. Mixes containing both CRCA and CRMMA showed a drop in splitting tensile strength of 20% for an overall replacement ratio of 37.5% (volumetric proportion of 1 CRMMA: 2 CRCA).

The coarse RAC mixes showed a linear decrease of their modulus of elasticity that was related to the replacement ratio of coarse natural aggregates (CNA) with coarse recycled aggregates (CRA). Evangelista and de Brito (2007) reached the same conclusion when using fine recycled concrete aggregates. This was due mostly to the lesser compacity of CRA, which is linked to hardened cement paste adhering to the original

CNA (both this paste and the mortar are more deformable than stone). This effect is even more pronounced for CRMMA because the ceramics have lower density than stone. The maximum decrease in the modulus of elasticity (-22.2%) in the mixes with 50% of CRMMA was similar to that observed in the tensile strength (-20.1%).

Concrete shrinkage was greatly affected by the incorporation of CRA, albeit to different degrees, depending on the nature and overall percentage incorporation in the mix. The mixes with up to 25% CRCA showed no significant differences in shrinkage from that of the reference concrete (RC), i.e. without CRA. The difference was practically constant at around 30% for percentages of 50% and 100%. Santos et al. (2002) found a similar increase when using 100% of CRCA.

The corresponding mixes had lower shrinkage than the RC up to CNA/CRMMA replacement ratios of 25%. This can be explained by the lower autogenous shrinkage of these mixes (because of free water accumulated in the CRMMA pores) in the early ages, with direct influence on the long-term shrinkage performance.

Mixes with simultaneous incorporation of CRCA and CRMMA showed a long-term performance similar to that of the RC until a total replacement ratio of 18.75% (mix C6.25CM15.5C), with lower values in the early ages. Compared with the RC, the shrinkage increment tends to reach around 50% for higher replacement ratios.

The conclusions drawn in this research increase existing knowledge on the performance of concrete with two types of CDW recycled aggregates. It is expected that the use of CDW in concrete production will significantly increase. This research would clearly benefit from the study of concrete with recycled aggregates coming from actual CDW recycling firms and/or plants.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of ICIST Research Institute, IST, Technical University of Lisbon and the FCT (Foundation for Science and Technology).

REFERENCES

Barra, M., Vásquez, E. - The influence of retained moisture in aggregates from recycling on the properties of new hardened concrete. Waste Management 16 (1-3), 1996, pp. 113-117.

Comité Euro-International du Béton - Model Code 1990: Design code. Thomas Telford Services Ltd, 1990.

De Brito, J., Pereira, A.S., Correia, J. - Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates. Cement and Concrete Composites 27 (4), 2005, pp. 429-433.

De Pauw, P., Thomas, P., Vyncke, J., Desmyter, J. - Shrinkage and creep of concrete with recycled materials as coarse aggregates. Sustainable Construction: Use of Recycled Concrete Aggregates, Thomas Telford, London, 1998, pp. 213-225.

EN 206-1, European Committee for Standardization, "Concrete - Part 1: Specification, performance, production and conformity", Brussels, 2000.

EN 933-1, European Committee for Standardization, "Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method", Brussels, 1997.

EN 933-2, European Committee for Standardization, "Tests for geometrical properties of aggregates - Part 2: Determination of particle size distribution - Test sieves, nominal size of apertures", Brussels, 1995.

EN 1097-2, European Committee for Standardization, "Tests for mechanical and physical properties of aggregates - Part 2: Methods for the determination of resistance to fragmentation", Brussels, 1998.

EN 1097-3, European Committee for Standardization, "Tests for mechanical and physical properties of aggregates - Part 3: Determination of loose bulk density and voids", Brussels, 1998.

EN 1097-6, European Committee for Standardization, "Tests for mechanical and physical properties of aggregates - Part 6: Determination of particle density and water absorption", Brussels, 2000.

EN 12350-2, European Committee for Standardization, "Testing fresh concrete - Part 2: Slump-test", Brussels, 2009.

EN 12350-6, European Committee for Standardization, "Testing fresh concrete - Part 6: Density", Brussels, 2009.

EN 12390-3, European Committee for Standardization, "Testing hardened concrete - Part 3: Compressive strength of test specimens", Brussels, 2003.

EN 12390-6, European Committee for Standardization, "Testing hardened concrete - Part 6: Tensile splitting strength of test specimens", Brussels, 2009.

Evangelista, L., de Brito, J. - Mechanical behaviour of concrete made with fine recycled concrete aggregates. Cement and Concrete Composites 29 (5), 2007, pp. 397-401.

Ferreira, L., de Brito, J., Barra, M. - Influence of pre-saturation of recycled coarse concrete aggregates on structural concrete's mechanical and durability properties. Magazine of Concrete Research 63 (8), 2011, pp. 617-627.

Gomes, M., de Brito, J. - Structural concrete with incorporation of concrete and ceramic aggregates: durability performance. Materials and Structures 42 (5), 2009, pp. 663-675.

Gonçalves, P., de Brito, J. - Recycled Aggregate Concrete (RAC) - Comparative analysis of existing specifications. Magazine of Concrete Research 62 (5), 2010, pp. 339-346.

Katz, A. - Use of recycled concrete aggregate in high-strength concrete. Cement and

Concrete Research 33 (5), 2003, pp. 703-711.

Kou, S., Poon, C., Chan, D. - Properties of steam cured recycled aggregate fly ash concrete. Use of Recycled Materials in Buildings and Structures, International RILEM Conference, Barcelona, 2004, pp. 590-599.

Limbachiya, M., Leelawat, T., Dhir, R. - Use of recycled concrete aggregate in high-strength concrete. Materials and Structures 33 (9), 2000, pp. 574-580.

LNEC E223, Portuguese National Laboratory of Civil Engineering standard, "Aggregates: Determination of volumetric index" *(in Portuguese)*, Lisbon, 1968.

LNEC E237, Portuguese National Laboratory of Civil Engineering standard, "Aggregates: Wear test machine in Los Angeles" *(in Portuguese)*, Lisbon, 1970.

LNEC E397, Portuguese National Laboratory of Civil Engineering standard, "Hardened concrete: Determination of the modulus of elasticity in compression" *(in Portuguese)*, Lisbon, 1993.

LNEC E398, Portuguese National Laboratory of Civil Engineering standard, "Hardened concrete: Determination of shrinkage and expansion" *(in Portuguese)*, Lisbon, 1993.

Matias, D., de Brito, J., Rosa, A., Pedro, D. - Mechanical properties of concrete produced with recycled coarse aggregates - Influence of the use of superplasticizers, Construction and Building Materials 44, 2013a, pp. 101-109.

Matias, D., de Brito, J., Rosa, A., Pedro, D. - Durability of concrete with recycled coarse aggregates: Influence of superplasticizers, Journal of Materials in Civil Engineering, 2013b, submitted for publication.

Muthmann, R. - Waste generated and treated in Europe - Data 1991-2001 [online]. European Communities, Luxembourg, cited April 2006. Available from: http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-55-03-471/EN/KS-55-03-471-EN.PDF.

Oliveira, M., Assis, C., Wanderley, A. - Study on compressed stress, water absorption and modulus of elasticity of produced concrete made by recycled aggregate. Use of Recycled Materials in Buildings and Structures, International RILEM Conference, Barcelona, 2004, pp. 636-642.

Olorunsogo, F.T. - Early age properties of recycled aggregate concrete. International Seminar on Exploiting Waste in Concrete, University of Dundee, Scotland, 1999, pp. 163-170.

Poon, C.S., Shui, Z.H., Lam, L., Fok, H., Kou, S.C. - Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. Cement and Concrete Research 34 (1), 2004, pp. 31-36.

Santos, R., Branco, F.A., de Brito, J. - Compressive strength, modulus of elasticity and drying shrinkage of concrete with coarse recycled concrete. XXX IAHS World Congress on Housing, Coimbra, Portugal, 2002, pp. 1685-1691.

Santos, R., Branco, F.A., de Brito, J. - Mechanical properties of concrete with coarse recycled aggregates. Structural Engineering International (IABSE) 14 (3), 2004, pp. 213-215.

Symonds - Construction and demolition waste management practices and their economic impact. Report to DGXI, European Commission, Brussels, 1999.

FIGURE CAPTIONS

Figure 1. Concrete mixes’ composition

Figure 2. Average concrete ultimate compressive stress as a function of CRCA incorporation ratio

Figure 3. Average concrete ultimate compressive stress as a function of CRMMA in-corporation ratio

Figure 4. Average concrete ultimate compressive stress as a function of CRCA and CRMMA simultaneous incorporation ratio

Figure 5. Concrete compressive strength evolution in the second testing stage

Figure 6. Linear regression of concrete splitting tensile strength as a function of CRM-MA incorporation ratio

Figure 7. Linear regression of concrete modulus of elasticity as a function of CRCA incorporation ratio

Figure 8. Linear regression of concrete modulus of elasticity as a function of CRMMA incorporation ratio

Figure 9. Shrinkage evolution of the concrete mixes with incorporation of CRCA in the first testing stage

Figure 10. Shrinkage evolution of the concrete mixes with incorporation of CRMMA in the first testing stage

Figure 11. Shrinkage evolution of the concrete mixes with simultaneous incorporation of CRCA and CRMMA in the first testing stage

Figure 12. Relative shrinkage coefficients (coarse RAC compared with RC) in the second testing stage

TABLE CAPTIONS

Table 1. CDW production in the EU by country (data from (Muthmann, 2006))

Table 2. Tests on aggregates

Table 3. $(w/c)_{ef}$ ratio and slump values for all concrete mixes

Table 4. Concrete bulk density

Table 5. Concrete 28 days compressive strength in the first testing stage

Table 6. Concrete 7 days compressive strength in the second testing stage

Table 7. Concrete 28 days compressive strength in the second testing stage

Table 8. Concrete 56 days compressive strength in the second testing stage

Table 9. Concrete 28 days splitting tensile strength

Table 10. Concrete 28 days modulus of elasticity

Table 1

Country	Average CDW production (1000 tonnes)	Average annual growth	Time scale	Population in 2005 (millions of inhabitants)	*Per capita* production (kg/person)
Belgium	6 559	n/a	1994	10.4	631
Denmark	2 787	6.05%	1992-2000	5.4	516
Germany	238 580	2.07%	1996-2000	82.5	2 892
Greece	1 898	3.90%	1996-2000	11.1	171
Spain	22 000	n/a	1991	43.0	512
France	24 300	-0.05%	1991-1997	59.9	406
Ireland	2 012	27.19%	1995-1998	4.1	491
Italy	26 226	-4.20%	1991-1999	58.5	448
Luxembourg	4 359	42.16%	1997-1999	0.5	8 717
Netherlands	15 604	4.33%	1990-2001	16.3	957
Austria	27 500	n/a	1999	8.2	3 354
Finland	33 545	4.12%	1997-1999	5.2	6 451
United Kingdom	70 625	0.39%	1990-1999	60.0	1 177
Norway	1 840	-3.74%	1990-2000	4.6	400
Switzerland	6 393	n/a	1998	7.5	852
Cyprus	555	-2.34%	1990-1999	0.7	793
Czech Republic	8 486	16.55%	1998-2001	10.2	832
Estonia	294	16.08%	1995-2000	1.3	226
Latvia	39	n/a	2001	2.3	17
Lithuania	231	10.00%	2000-2001	3.4	68
Malta	970	-2.29%	1990-2001	0.4	2 424
Poland	668	2.94%	1998-2001	38.2	17
Romania	623	27.68%	1995-2000	21.7	29
Slovakia	477	-6.80%	1998-2000	5.4	88
Slovenia	427	35.64%	1995-2001	2.0	213
Croatia	290	n/a	2000	4.4	66
Total	497 285	-	-	467.2	1 064

Table 2

Aggregate	Fine sand	Coarse sand	Gravel 1	Gravel 2	CRCA	CRMMA
Dry-oven particles bulk density (kg/dm^3)	-	-	2.57	2.55	2.45	2.16
Saturated surface dry particles bulk density (kg/dm^3)	-	-	2.59	2.57	2.53	2.30
Water absorption (%)	-	-	2.21	2.29	8.49	16.34
Loose bulk density (kg/dm^3)	1.41	1.50	1.53	1.53	1.30	1.20
Los Angeles wear (%)	-	-	28.52	28.52	37.96	65.47
Volume index	-	-	0.95-0.96	0.98-1.05	0.77-0.81	0.92-1.22

Table 3

	RC	C12.5C	C25C	C50C	C100C	C6.25CM	C12.5CM	C25CM	C50CM	C6.25CM12.5C	C12.5CM25C	C25CM50C
$(w/c)_{apparent}$	0.43	0.44	0.44	0.45	0.48	0.44	0.45	0.48	0.53	0.45	0.47	0.49
$(w/c)_{effective}$	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43
Slump (mm)	85	95	72	92	80	82	80	81	78	92	97	91

Table 4

Concrete mix	Density (kg/m^3)
RC	2366.3
C6.25CM12.5C	2352.3
C12.5CM25C	2342.3
C25CM50C	2307.3
C100C	2246.3
C50C	2350.9
C25C	2358.9
C12.5C	2364.9
C50CM	2224.9
C25CM	2330.9
C12.5CM	2302.0
C6.25CM	2394.0

Table 5

Concrete mix	f_c (MPa)						f_{cm} (MPa)
RC	47.38	47.64	44.52	52.16	48.13	43.8	47.27
C12.5C	43.14	46.67	47.87	47.73	46.93	47.24	46.60
C25C	46.62	*	45.07	45.33	46.00	46.27	45.86
C50C	49.86	50.50	51.30	47.37	51.60	48.13	49.79
C100C	48.49	50.98	47.07	51.20	50.27	*	49.60
C6.25CM	47.56	48.76	47.11	49.51	46.40	48.71	48.01
C12.5CM	43.12	45.36	44.35	43.04	*	44.46	44.07
C25CM	46.67	47.60	41.01	44.76	43.87	44.78	44.78
C50CM	34.16	35.50	37.95	35.99	38.87	34.27	36.12
C6.25CM12.5C	46.76	44.65	47.57	46.61	46.40	45.76	46.29
C12.5CM25C	35.42*	44.98	47.60	44.76	42.52	33.34*	44.96
C25CM50C	44.15	47.38	45.02	45.16	43.88	49.29	45.81

* - Readings ignored due to anomalous failure modes.

Table 6

	RC	C12.5CM25C	C25CM	C50C
F (kN)	845.1	954.8	801.3	1110
	847.3	906.2	820.6	978.1
	847.8	918.7	843.2	1025
f_c (MPa)	37.56	42.44	35.61	43.17
	37.66	40.28	36.47	38.04
	37.68	40.83	37.48	39.86
f_{cm} (MPa)	37.63	40.36	36.52	41.18

Table 7

	RC	C12.5CM25C	C25CM	C50C
F (kN)	955.7	1035	848.6	1213
	943.2	982.1	881.3	1242
	1014	1077	988.8	1181
	991.0	1087	931.2	1204
	990.3	1054	994.6	1154
f_c (MPa)	47.17	46.00	37.72	47.17
	48.30	43.65	39.17	48.30
	45.93	47.87	43.95	45.93
	46.82	48.31	41.39	46.82
	44.88	46.84	44.20	44.88
f_{cm} (MPa)	43.50	46.53	41.28	46.62

Table 8

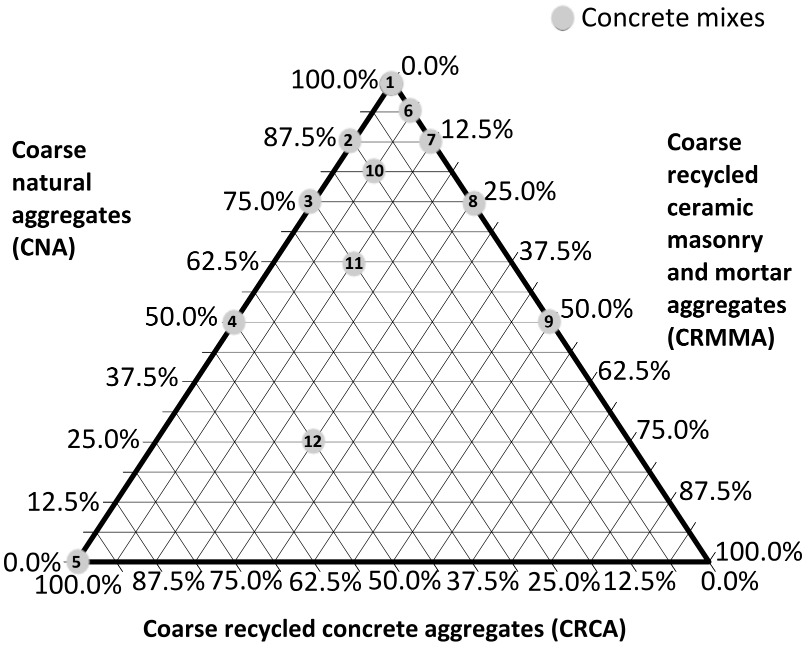
	RC	C12.5CM25C	C25CM	C50C
F (kN)	969	1113	1045	1218
	1047	1107	974	1239
f_c (MPa)	43.07	49.47	46.44	51.43
	46.53	49.20	43.30	52.31
f_{cm} (MPa)	44.80	49.33	44.87	51.87

Table 9

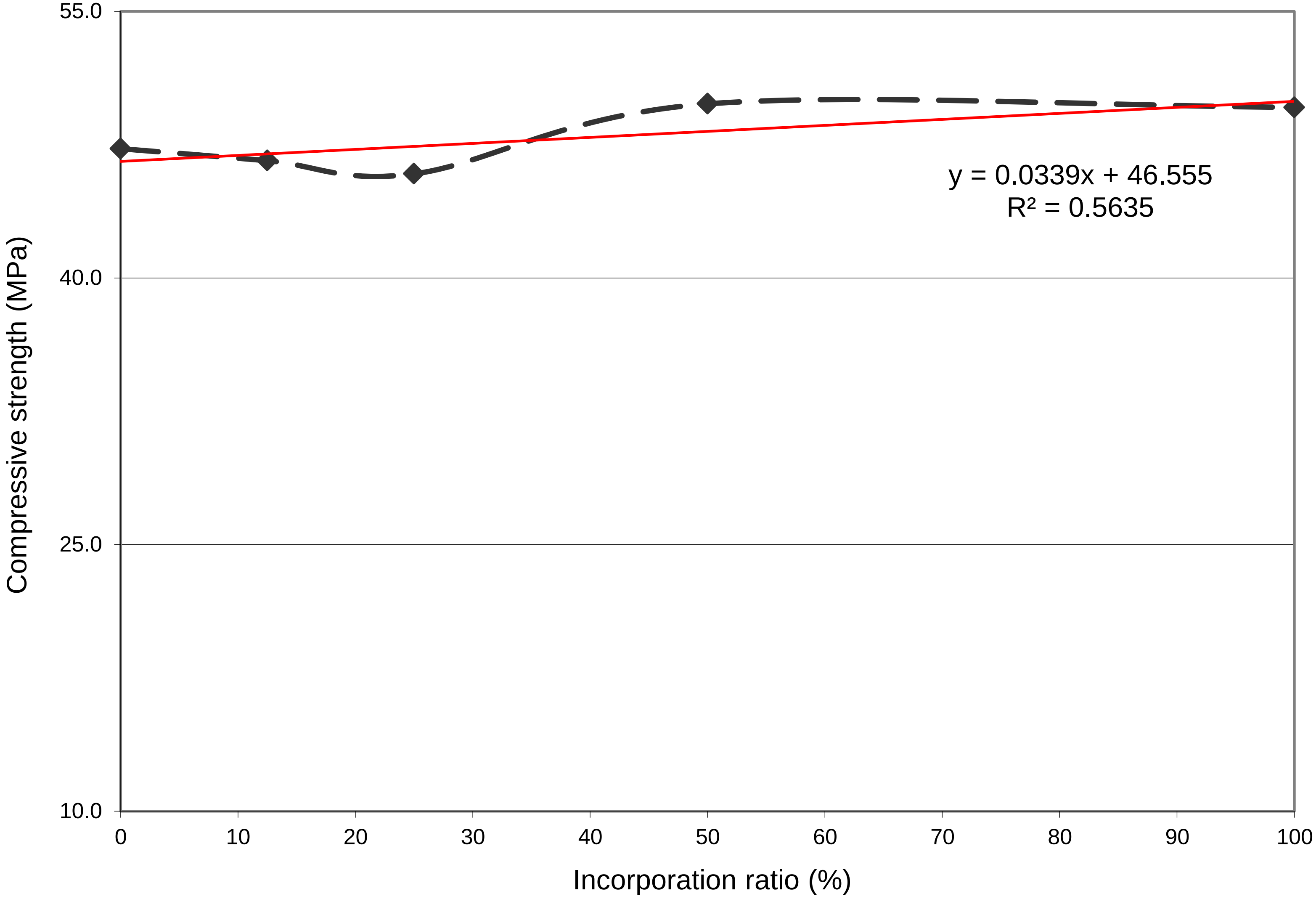
Concrete mix	Specimen 1	Specimen 2	Specimen 3	Average (MPa)	D (%)
RC	3.41	3.13	3.13	3.23	-
C50C	3.79	2.87	3.03	3.23	0.2
C25CM	3.07	3.07	2.89	3.01	-6.6
C12.5CM25C	2.62	3.05	2.28	2.65	-17.9
C100C	3.50	3.05	2.70	3.08	-4.5
C50CM	2.58	2.55	2.61	2.58	-20.1

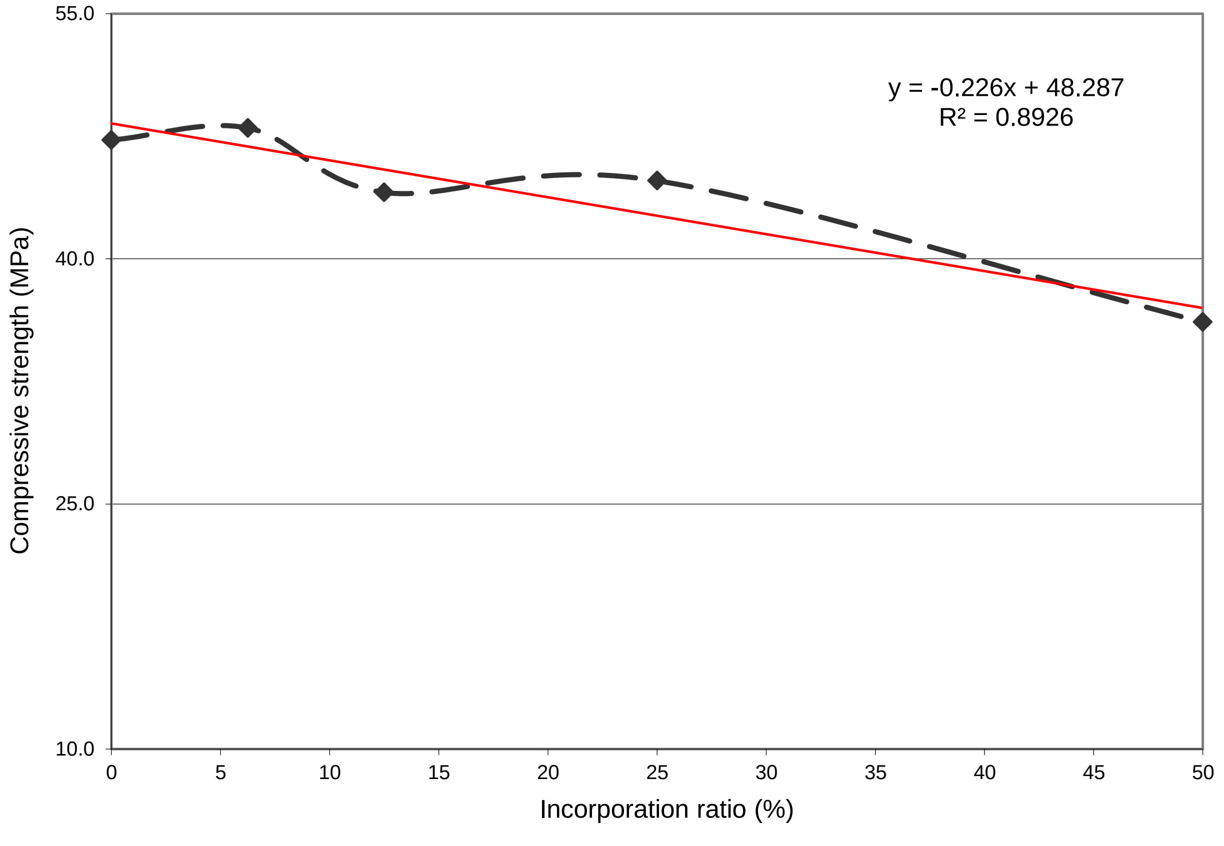
Table 10

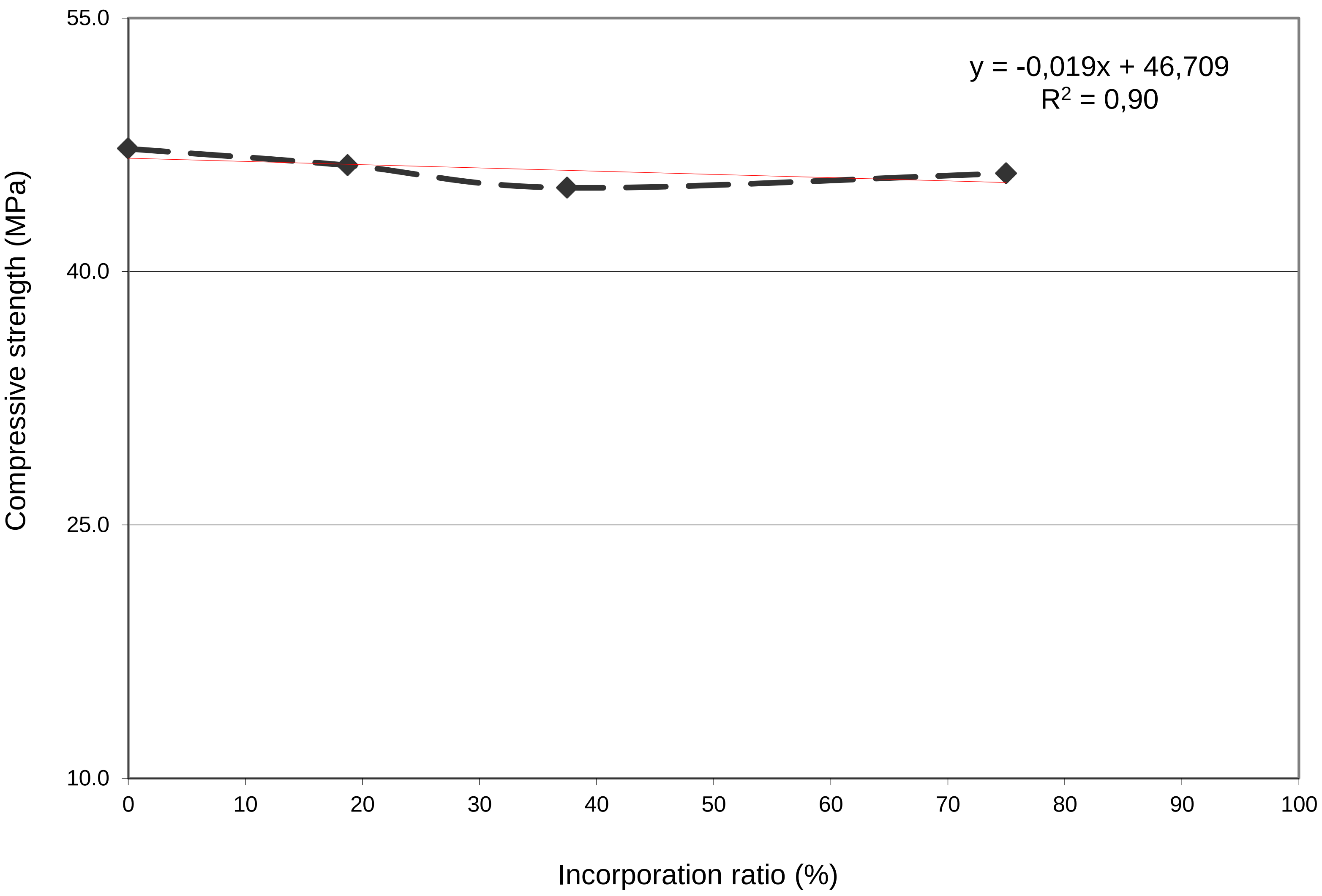
Concrete mix	Specimen 1	Specimen 2	Specimen 3	Average (GPa)	D (%)
RC	43.5	38.7	40.5	40.9	-
C50C	35.8	37.9	36.5	36.7	-10.2
C25CM	40.2	30.0	33.2	34.5	-15.8
C12.5CM25C	34.2	35.5	33.1	34.3	-16.2
C100C	30.2	27.1	28.5	28.6	-30.0
C50CM	29.7	32.4	33.0	31.7	-22.2

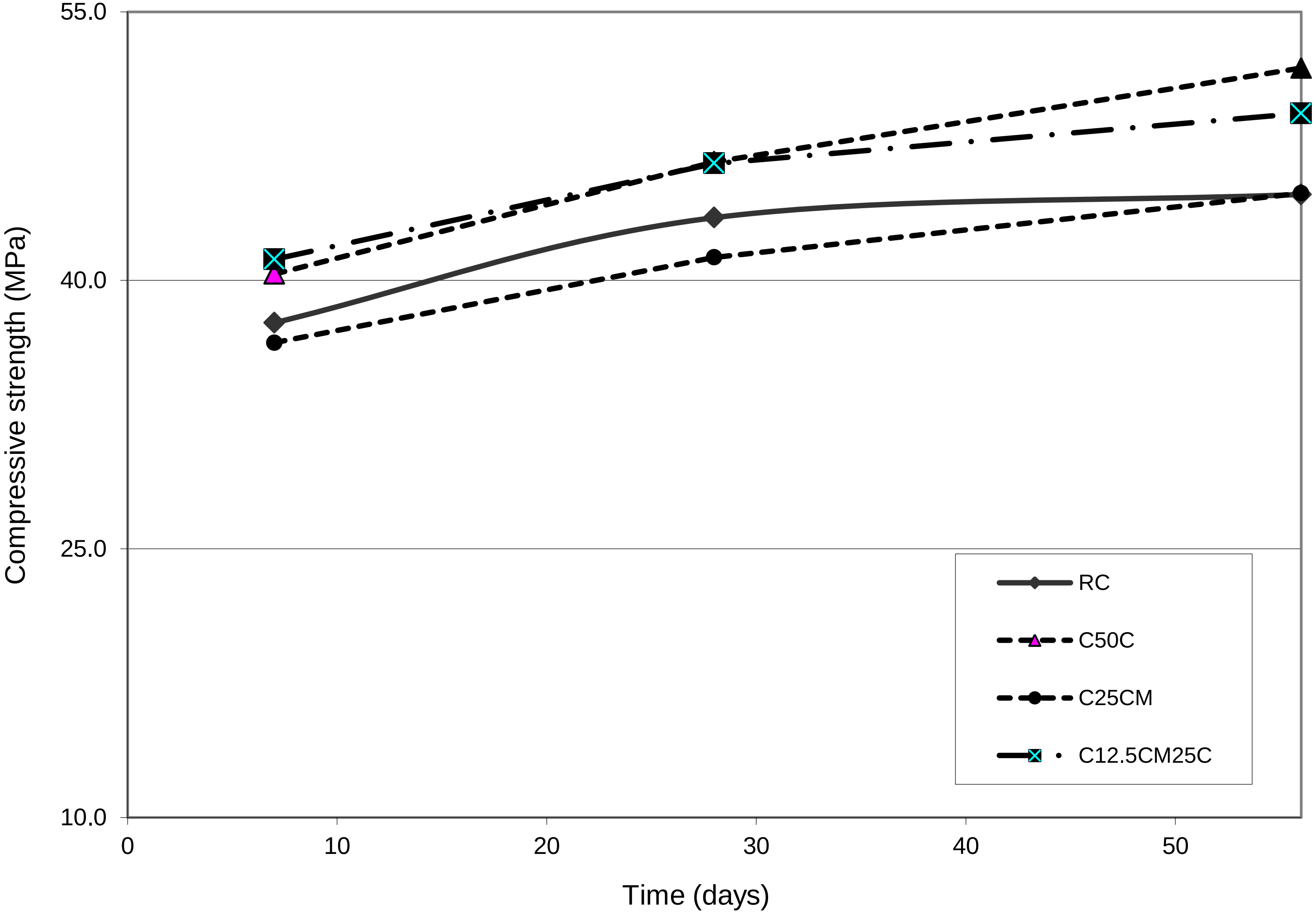


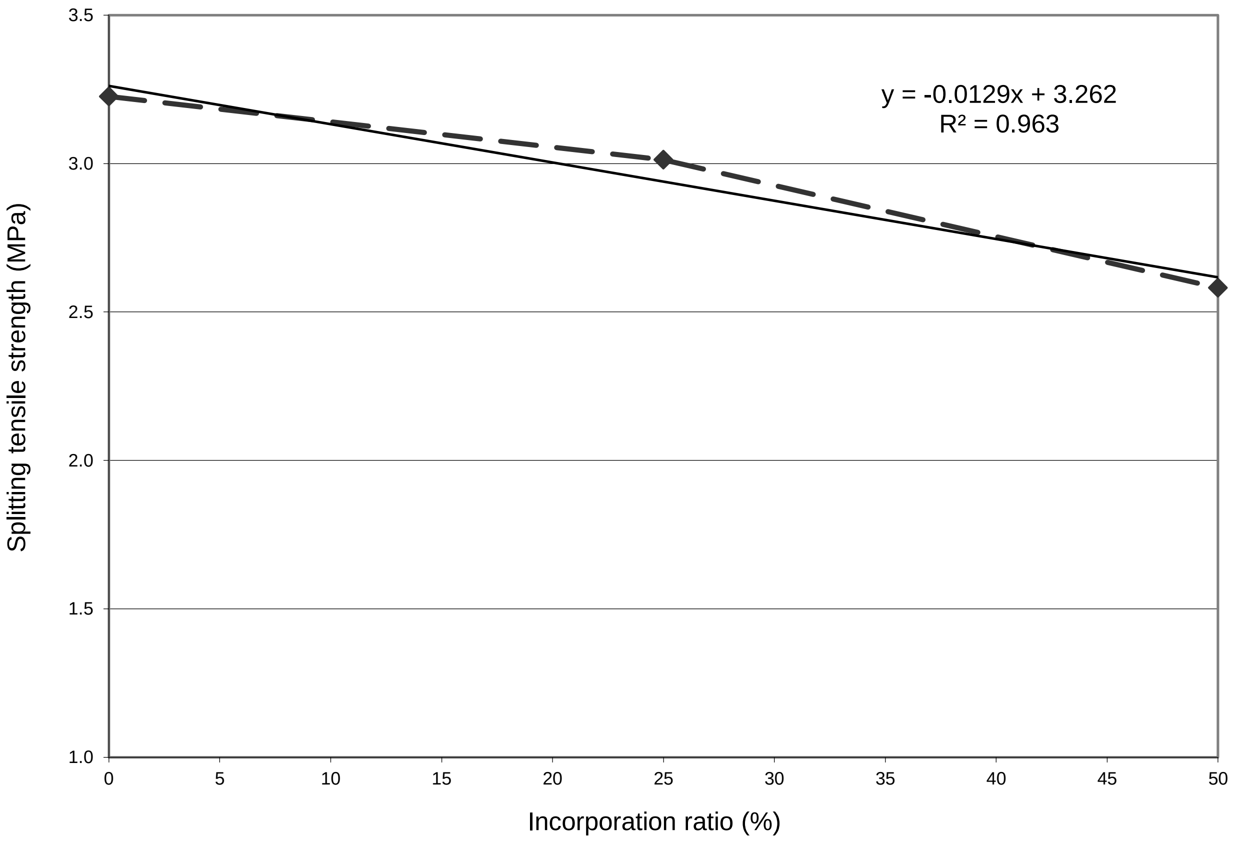
	1	2	3	4	5	6	7	8	9	10	11	12
Concrete mixes' composition	RC	C12.5C	C25C	C50C	C100C	C6.25CM	C12.5CM	C25CM	C50CM	C6.25CM12.5C	C12.5CM25C	C25CM50C

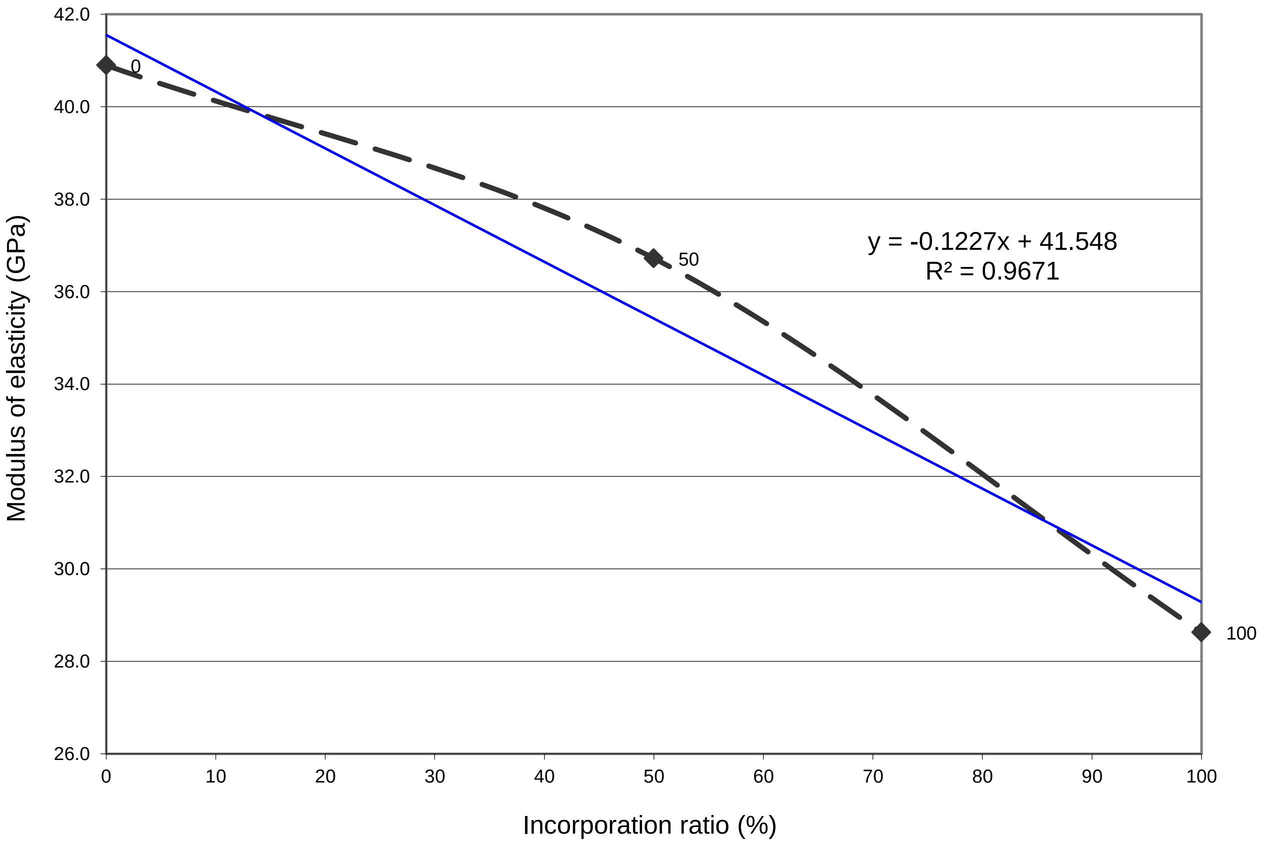

55.0
40.0
25.0
10.0
Compressive strength (MPa)
0
10
20
30
40
50
60
70
80
90
100
Incorporation ratio (%)
y = 0.0339x + 46.555
R² = 0.5635


55.0
40.0
25.0
10.0
Compressive strength (MPa)
0
5
10
15
20
25
30
35
40
45
50
Incorporation ratio (%)
y = -0.226x + 48.287
R² = 0.8926

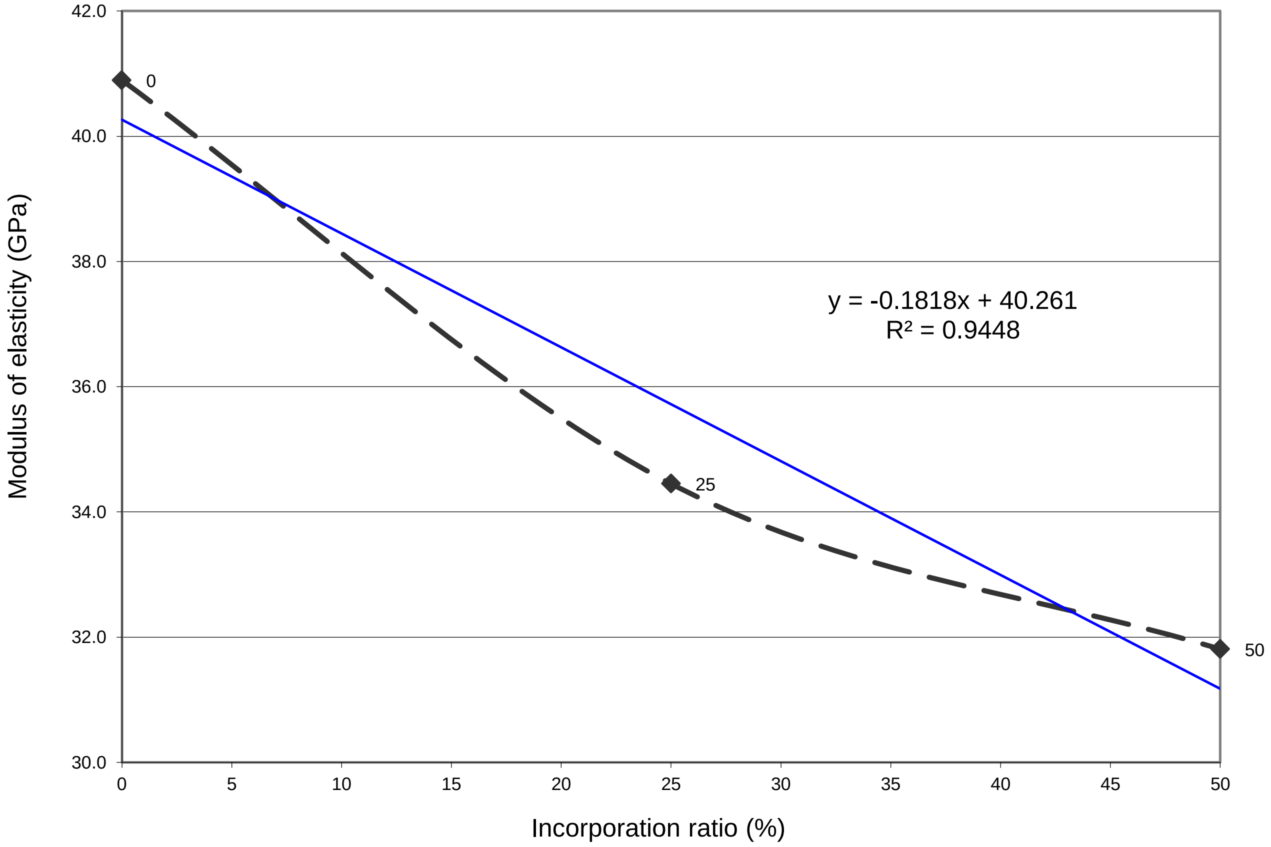

y = -0,019x + 46,709
R^2 = 0,90
Compressive strength (MPa)
55.0
40.0
25.0
10.0
0
10
20
30
40
50
60
70
80
90
100
Incorporation ratio (%)


55.0
40.0
25.0
10.0
Compressive strength (MPa)
0
10
20
30
40
50
Time (days)
RC
C50C
C25CM
C12.5CM25C

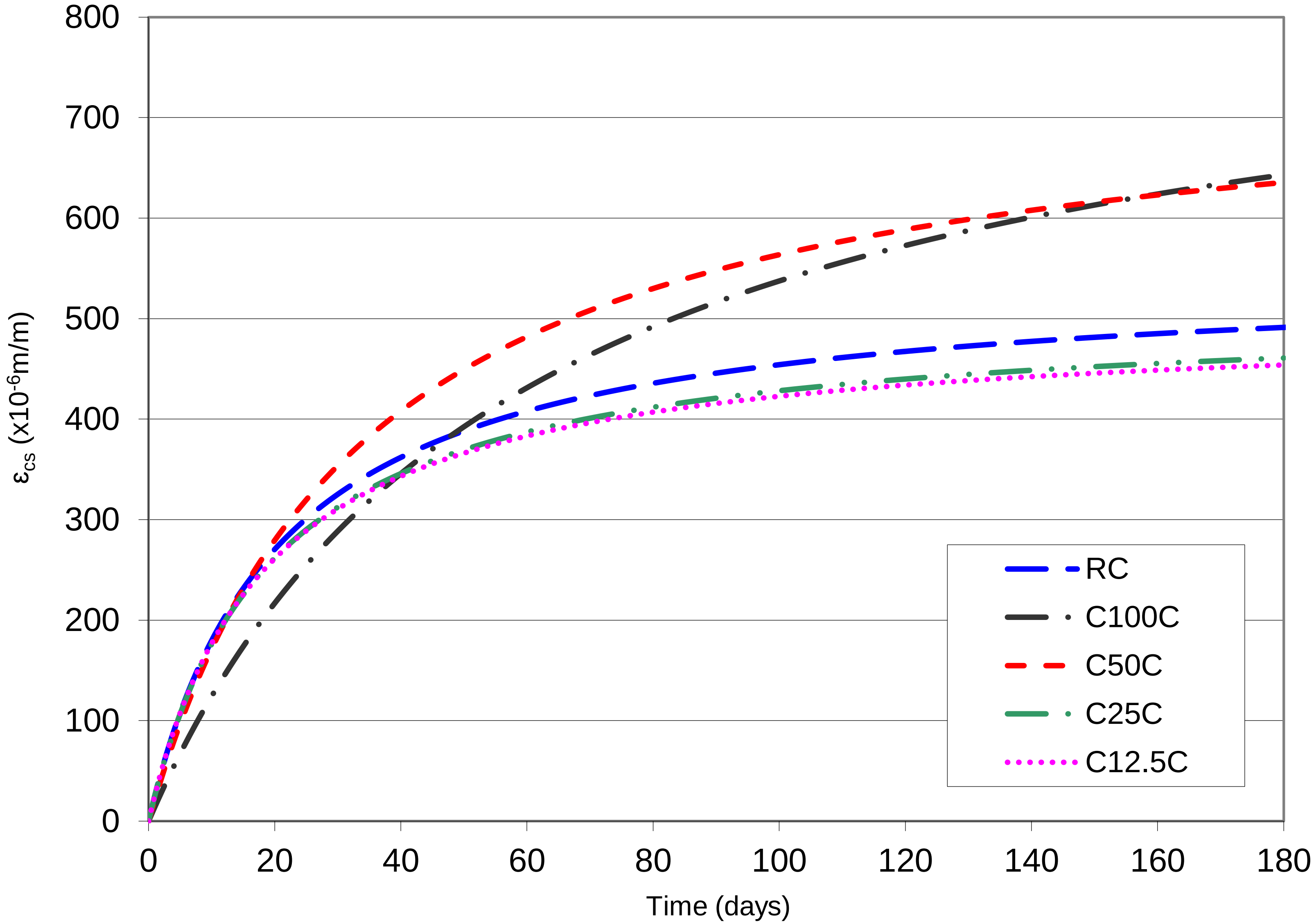

y = -0.0129x + 3.262
R² = 0.963
Splitting tensile strength (MPa)
3.5
3.0
2.5
2.0
1.5
1.0
0
5
10
15
20
25
30
35
40
45
50
Incorporation ratio (%)



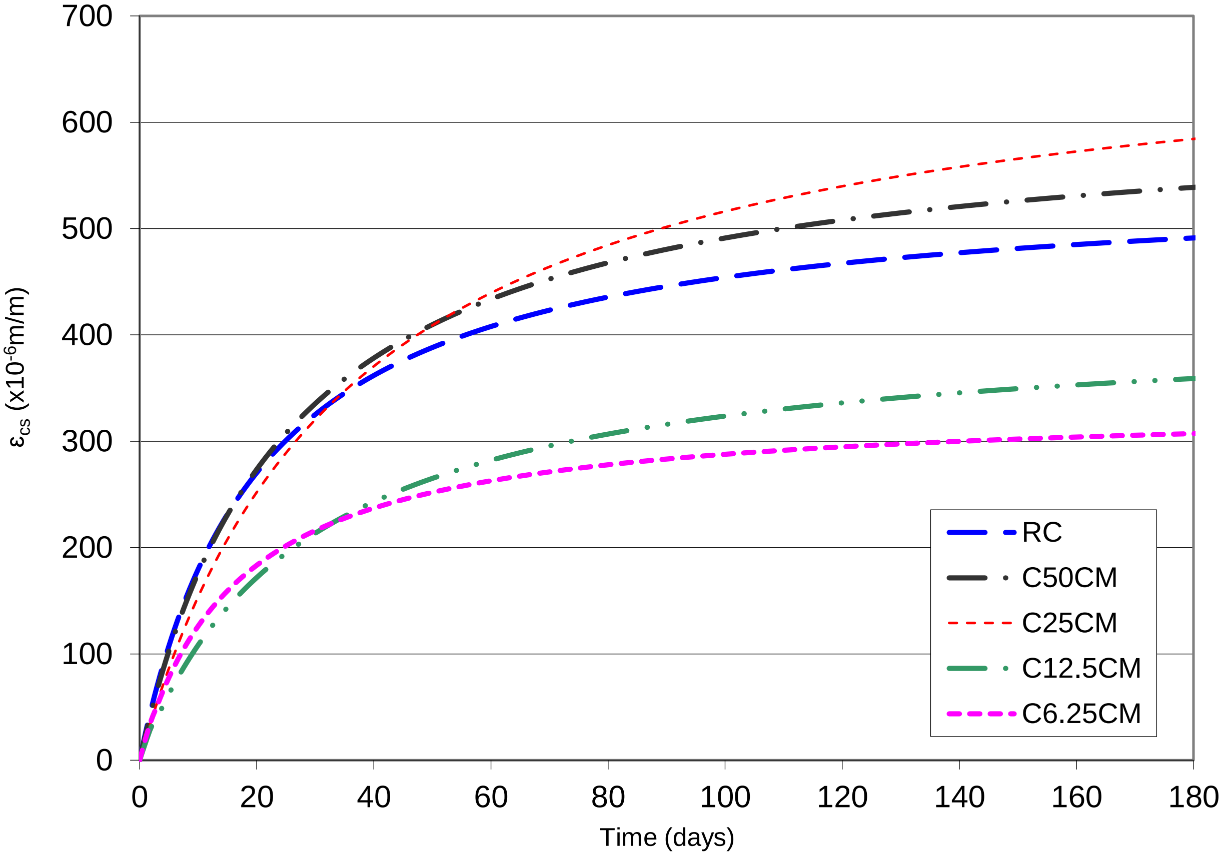
42.0
40.0
38.0
36.0
34.0
32.0
30.0
28.0
26.0
Modulus of elasticity (GPa)
0
50
100
y = -0.1227x + 41.548
R² = 0.9671
0
10
20
30
40
50
60
70
80
90
100
Incorporation ratio (%)



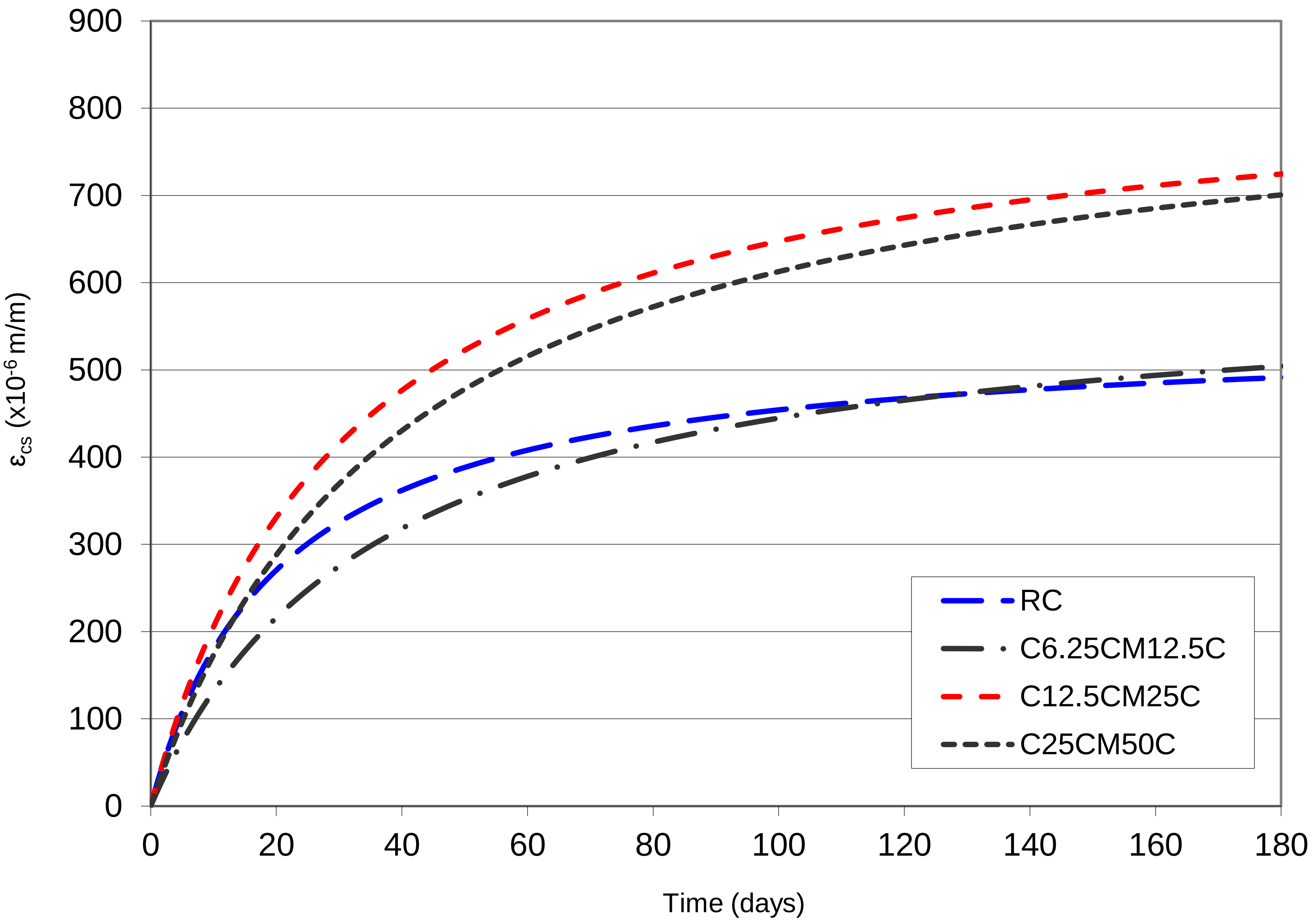
42.0
40.0
38.0
36.0
34.0
32.0
30.0
Modulus of elasticity (GPa)
0
25
50
y = -0.1818x + 40.261
R² = 0.9448
0
5
10
15
20
25
30
35
40
45
50
Incorporation ratio (%)



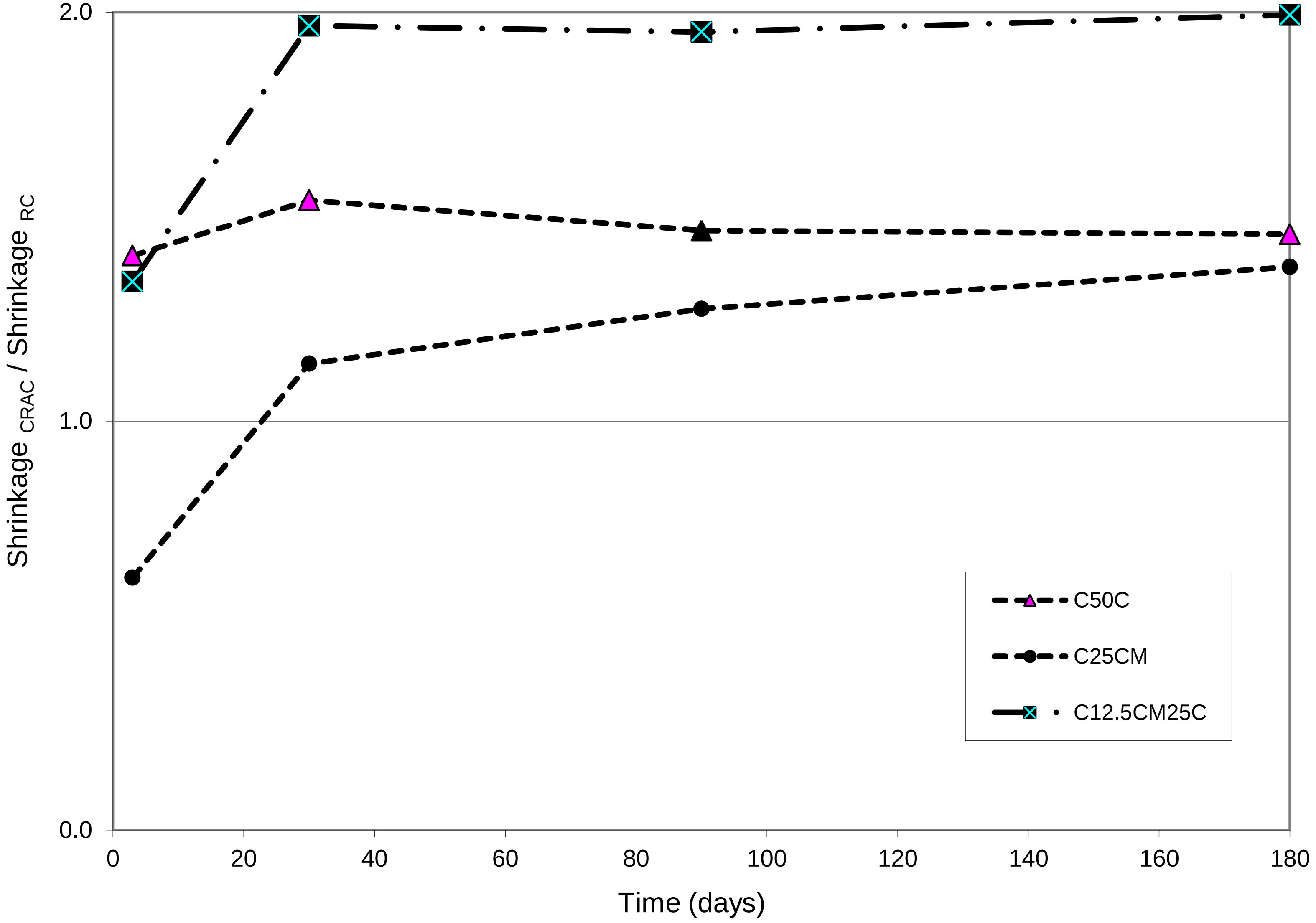
800
700
600
500
400
300
200
100
0
ε_{cs} (x10^{-6}m/m)
0
20
40
60
80
100
120
140
160
180
Time (days)
RC
C100C
C50C
C25C
C12.5C



700
600
500
400
300
200
100
0
ε_{cs} (x10^{-6}m/m)
0
20
40
60
80
100
120
140
160
180
Time (days)
RC
C50CM
C25CM
C12.5CM
C6.25CM



900
800
700
600
500
400
300
200
100
0
ε_{cs} (x10^{-6} m/m)
0
20
40
60
80
100
120
140
160
180
Time (days)
RC
C6.25CM12.5C
C12.5CM25C
C25CM50C


2.0
1.0
0.0
0
20
40
60
80
100
120
140
160
180
Time (days)
Shrinkage CRAC / Shrinkage RC
C50C
C25CM
C12.5CM25C