A comparative study of the mechanical and life cycle assessment of high-content fly ash and recycled aggregates concrete

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Abstract:

In this paper, an extensive experimental work is made to understand the mechanical behaviors, environmental impacts (EI) and resources use of concrete mixtures containing high amounts of fly ash (FA) and/or recycled aggregates (RA). Then, the results of this study are compared with previous studies, and also non-expected results and missing information from those studies are highlighted. For that purpose, the Life Cycle Assessment (LCA) methodology was used to determine the most influential factors, resources use (e.g. non-renewable energy consumption - PE-NRe) and EI (e.g. potential global warming - GWP) for probable scenarios in the center of Portugal, according to EN 15804 and ISO 14040. In addition, the mechanical behavior (compressive and tensile strength, and modulus of elasticity) are also considered. The results show that the use of RA negatively affects all the mechanical parameters of concrete when the binder content is kept constant. The use of FA also affects the mechanical performance of concrete except for the modulus of elasticity. In addition, according to the results of this study, the GWP and PE-NRe of concrete mixtures seem not to be considerably affected by the incorporation of RA. However, in previous studies, the GWP and PE-NRe of RA concrete strongly depends on the transportation scenario. The LCA of concrete significantly decreases with the use of FA, regardless of the transportation scenario. According to the relationship made based on the results of this study (same LCA scenario) and previous studies (different LCA scenarios), there are no clear relationships between the mechanical behaviors, and GWP and PE-NRe of concrete mixtures with and without “RA and FA” because the incorporation of each of the non-traditional materials differently affects each characteristic of concrete and LCA results may be different for other approaches or assumed scenarios in life cycle inventory modelling. Thus, an optimization method is needed to find the optimum concrete in terms of mechanical performance, EI and resources use point of view.

Keywords: Concrete; Compressive strength; Energy consumption; Global warming; Modulus of elasticity; Tensile strength.

Abbreviations: CRA - coarse recycled aggregates; E_{cm} - modulus of elasticity; EI - environmental impacts; FA - fly ash; f_{cm} - compressive strength; f_{ctm} - splitting tensile strength; FRA - fine recycled aggregates; GWP - potential global warming; NA - natural aggregates; PE-NRe - non-renewable energy consumption; RA - recycled aggregates; SP - superplasticizer.

1 Introduction

After water, concrete is one of the most demanded materials worldwide. Therefore, it has a significant influence on environmental impacts (EI) and many alternative materials such as construction demolition wastes [1-9] and/or cementitious materials [10-14] have been proposed to be used instead of traditional materials in order to decrease the EI of concrete.

Generally, non-renewable energy consumption (PE-NRe) and potential global warming (GWP) are the most influential factors on the EI of any product [15]. One way to decrease them is by using non-conventional materials. Therefore, this study focuses on the effect of the incorporation ratio of both “construction demolition wastes”, such as fine recycled aggregates (FRA) and coarse recycled aggregates (CRA), and/or “cementitious materials”, such as fly ash (FA) on the GWP and PE-NRe of concrete. In addition, it is well-known that the compressive strength (f_{cm}), splitting tensile strength (f_{ctm}) and modulus of elasticity (E_{cm}) are some of the most important factors to evaluate the mechanical behavior of concrete. Therefore, this study pays particular attention to the effect of FA and recycled aggregates (RA) on the f_{cm}, f_{ctm} and E_{cm} of concrete.

An extensive literature review and experimental work were performed to understand the EI and mechanical behaviors of concrete containing high amounts of FA and/or FA. The reason for focusing on both aspects is that they are both considered important factors to identify a sustainable concrete [16, 17]. In other words, both characteristics need to be considered to aid the selection of the optimum concrete, namely in a green scenario [18]. For example, by comparison with low-strength concrete, high-strength concrete structural elements need smaller cross-section, and this directly changes the total volume of concrete needed to build the building [19] and its total EI as a consequence. On the other hand, a high cement content or superplasticizer (SP) need to be used to obtain high-strength concrete. Previous studies concluded that cement is one of the essential contributors to the total CO_2 emissions of concrete [20-22]. Thus, to understand the effect of any non-traditional material (e.g. FRA, CRA and FA), the best concrete from one point of view only (e.g. EI, resources use and mechanical performance) may not be a good solution in terms of sustainability. Therefore, a specific method like CONCRE***Top*** (A multi-criteria decision method for concrete optimization - [18]) may be required to choose the optimum concrete.

This study provides a comprehensive synthesis of previous studies on the effect of FA and/or RA on mechanical behavior and EI of concrete. The results show that the individual influence of non-traditional products on concrete has been comprehensively studied from different points of view, e.g. mechanical behavior and EI [23-27]. However, most of the researchers studied the effect of high incorporation ratio of RA and FA from one viewpoint only (f_{cm} or EI) of either low- or high-strength concrete, and there is still a gap between the mentioned aspects as a result of the indirect relationship between them, especially when both non-traditional products are used in concrete. Thus, the second part of this study (experimental work) is to fulfil the mentioned gap, namely compare the individual and combined effects of both FA and RA in terms of most mechanical properties (f_{cm}, f_{ctm}, E_{cm}) or EI of high- and low-strength concrete.

2 Materials and methods

As stated above, the objective of current study is to analyze the influence of different incorporation ratios of RA and/or FA on the EI and mechanical properties of concrete. Therefore, an experimental campaign was made to understand the mechanical characteristics (e.g. f_{cm}, f_{ctm} and E_{cm}) of concrete at different ages (0.2-12 months). Concerning the EI (e.g. GWP and PE-NRe), the Simapro software was adopted to calculate the data obtained from EPD reports, site specific data, and other individual studies. The results of the current study were compared with those of previous investigations after preparing an extensive literature review. It is known that durability performance is also an important parameter on the service life of concrete, but we only considered the mechanical performance because it is already studied by the same authors of this study.

The concrete mixtures were produced with ordinary Portland cement (CEM 42.5 R - OPC), FA (type F), CRA and FRA (aggregates made with 100% of uncontaminated crushed concrete), and fine (natural silica sand) and coarse (crushed limestone) natural aggregates (NA). The binder content (OPC and FA) was similar for all concrete mixtures (350 kg/m^3). Workability was also kept constant (S2). Superplasticizer (SP) was adopted in almost half of the concrete mixtures to analyze its influence on their mechanical properties and EI. The water to binder ratio (w/b) of traditional concrete with ($M1_{sp}$) and without (M1) SP (1% of binder's weight) was 0.42 and 0.53, respectively. Different quantities of FRA, FA and CRA, without and with SP were used in the concrete mixtures (Table 1). The mix compositions and the properties of the materials were briefly presented to avoid repetition, since the details regarding the materials' properties, concrete mix design (e.g. water, binder and aggregate contents of each mix) and mixing procedure of the concrete mixtures were already shown in previous works [17, 28].

Table 1 - Concrete mixtures composition

CRA		0%			100%		
FRA		0%	50%	100%	0%	50%	100%
FA	0%	$M1_{sp}$ and M1	M2	$M3_{sp}$ and M3	$M10_{sp}$ and M10	M11	$M12_{sp}$ and M12
	30%	M4	$M5_{sp}$ and M5	M6	M13	$M14_{sp}$ and M14	M15
	60%	$M7_{sp}$ and M7	M8	$M9_{sp}$ and M9	$M16_{sp}$ and M16	M17	$M18_{sp}$ and M18

The mechanical properties (f_{cm}, E_{cm} and f_{ctm}) and EI (PE-NRe and GWP) of the mixtures were experimentally and analytically determined according to the details and standards [29-33] given in Table 2.

Table 2 - Standards and details for each selected category

Categories	Abbreviation	Units	Size	Standard
Compressive strength	$f_{cm,cube}$	MPa	150x150 mm	[29]
Modulus of elasticity	E_{cm}	GPa	Ø150x300 mm	[30]

Splitting tensile strength	f_{ctm}	MPa	150x300 mm	[31]
Global warming potential	GWP	kg CO_2 eq	Cubic meter	LCA methodology [32, 33]
Non-renewable primary energy resources	PE-NRe	MJ	Cubic meter	LCA methodology [32, 33]

As for life-cycle assessment, the most reasonable scenarios for the Lisbon region in Portugal (Figure 1), from cradle to gate (A1-A3) based on EN 15804 [33] and ISO 14040 [32], were used to obtain the EI of each concrete mixture (Table 2). It is known that the total EI and energy consumption of concrete significantly depend on the transportation scenario. Thus, the LCA data for other transportation scenarios in Portugal (e.g. north and south of the country) can be determined by the methodology shown in [25]. Further details on life cycle analysis methodology are given in other studies [16-17].

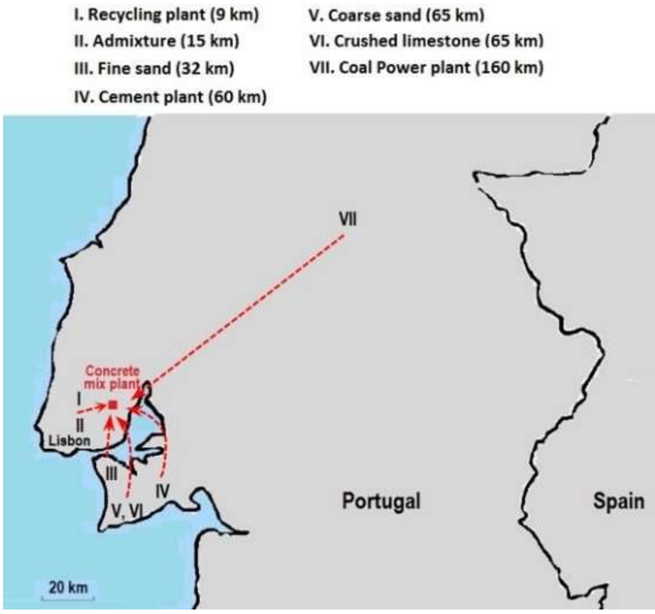


Figure 1 - Most common transportation scenario in the Lisbon region (Portugal)

3 Results and discussion

In this section, the individual and joint effects of high quantities of RA and FA on the f_{cm} (§3.1), f_{ctm} (§3.2), E_{cm} (§3.3) and EI (energy consumption and global warming - §3.4) of concrete are shown based on both the extensive experimental work (Table 3) and compared with the literature.

Table 3 - Mechanical behaviors and EI of the concrete mixtures

NO.	Mixtures	Details [a]	Age (days)															EI and resource use per m³	
			7			28			90			180			365				
			$f_{cm,cube}$ (MPa)	$f_{ctm,sp}$ (MPa)	Ecm (GPa)	$f_{cm,cube}$ (MPa)	$f_{ctm,sp}$ (MPa)	Ecm (GPa)	$f_{cm,cube}$ (MPa)	$f_{ctm,sp}$ (MPa)	Ecm (GPa)	$f_{cm,cube}$ (MPa)	$f_{ctm,sp}$ (MPa)	Ecm (GPa)	$f_{cm,cube}$ (MPa)	$f_{ctm,sp}$ (MPa)	Ecm (GPa)	GWP kg CO_2 eq	PE-NRe MJ
1	M1	$FA_0F_0C_0$	50.7	3.8	-	55.8	4.3	43.8	59.0	4.7	45.1	59.1	4.7	45.9	61.3	4.7	47.0	3.62E+02	1.95E+03
2	M2	$FA_0F_{50}C_0$	41.0	3.0	-	46.2	3.8	39.0	50.0	4.1	39.1	50.4	4.2	40.2	52.0	4.3	41.4	3.61E+02	1.94E+03
3	M3	$FA_0F_{100}C_0$	37.4	2.8	-	45.0	3.5	34.7	47.5	3.7	36.3	50.0	3.9	37.9	51.5	4.0	39.0	3.60E+02	1.94E+03
4	M4	$FA_{30}F_0C_0$	31.0	1.8	-	40.2	3.0	41.4	55.7	4.2	46.3	56.6	4.3	49.2	60.0	4.5	50.3	2.69E+02	1.58E+03
5	M5	$FA_{30}F_{50}C_0$	27.5	1.5	-	36.4	2.9	38.3	49.0	3.9	41.0	51.7	4.2	43.9	57.2	4.5	46.3	2.68E+02	1.57E+03
6	M6	$FA_{30}F_{100}C_0$	25.1	1.4	-	34.0	2.6	32.4	46.4	3.6	37.6	48.6	3.8	40.4	54.2	4.1	43.2	2.67E+02	1.56E+03
7	M7	$FA_{60}F_0C_0$	17.7	1.1	-	24.0	2.3	38.0	35.3	3.3	42.1	37.6	3.5	45.0	42.2	3.6	46.1	1.76E+02	1.21E+03

8	M8	$FA_{60}F_{50}C_{0}$	17.3	1.1	-	23.6	2.3	34.1	33.4	3.2	37.3	38.3	3.5	40.2	42.5	3.9	41.8	1.74E+02	1.19E+03
9	M9	$FA_{60}F_{100}C_{0}$	15.4	0.9	-	21.5	2.2	32.3	30.9	3.1	34.2	35.3	3.4	37.4	40.0	3.8	41.4	1.74E+02	1.19E+03
10	M10	$FA_{0}F_{0}C_{100}$	45.5	3.4	-	51.9	4.2	37.1	56.5	4.6	39.0	57.1	4.7	40.4	59.2	4.7	41.4	3.31E+02	1.53E+03
11	M11	$FA_{0}F5_{0}C_{100}$	36.0	2.8	-	42.8	3.4	32.5	46.1	3.7	33.9	49.2	3.8	35.4	51.0	3.9	36.3	3.31E+02	1.53E+03
12	M12	$FA_{0}F_{100}C_{100}$	34.2	2.7	-	42.0	3.3	28.0	44.1	3.5	29.1	48.7	3.7	30.6	50.2	3.9	31.4	3.30E+02	1.53E+03
13	M13	$FA_{30}F_{0}C_{100}$	29.3	1.6	-	39.0	2.9	34.8	51.3	3.9	39.1	55.4	4.2	41.7	62.0	4.6	42.8	2.38E+02	1.16E+03
14	M14	$FA_{30}F_{50}C_{100}$	24.5	1.5	-	33.0	2.5	32.5	46.1	3.2	35.3	48.5	3.6	38.0	56.6	4.0	40.0	2.38E+02	1.15E+03
15	M15	$FA_{30}F_{100}C_{100}$	24.0	1.4	-	32.8	2.4	29.7	46.0	3.1	32.0	48.9	3.5	35.0	53.4	3.9	38.3	2.37E+02	1.15E+03
16	M16	$FA_{60}F_{0}C_{100}$	16.6	0.8	-	23.0	2.2	33.0	30.6	2.9	36.4	36.8	3.3	39.6	41.0	3.7	41.1	1.45E+02	7.83E+02
17	M17	$FA_{60}F_{50}$	14.3	0.8	-	21.1	1.7	29.4	30.1	2.5	31.7	34.8	2.7	34.3	38.8	3.0	36.7	1.45E+02	7.81E+02
18	M18	$FA_{60}F_{100}$	13.9	0.7	-	21.0	1.7	26.9	29.9	2.5	29.1	35.5	2.7	31.9	38.0	3.1	35.3	1.44E+02	7.79E+02
19	M1sp	$FA_{0}F_{0}C_{0sp}$	71.0	4.2	-	73.5	5.3	51.4	76.7	5.6	55.3	82.3	5.6	55.6	83.0	5.6	55.7	3.64E+02	1.98E+03
20	M3sp	$FA_{0}F_{100}C_{0sp}$	52.0	3.3	-	54.1	3.9	39.9	58.0	4.3	41.2	61.7	4.4	42.2	63.7	4.3	42.6	3.63E+02	1.97E+03
21	M5sp	$FA_{30}F_{50}C_{0sp}$	45.1	3.3	-	60.4	4.6	43.9	62.7	4.8	47.9	75.5	4.9	49.2	79.0	4.9	50.2	2.70E+02	1.61E+03
22	M7sp	$FA_{60}F_{0}C_{0sp}$	25.7	1.8	-	42.4	3.8	40.7	49.7	4.5	46.1	55.6	4.6	47.5	58.0	4.6	47.7	1.79E+02	1.25E+03
23	M9sp	$FA_{60}F_{100}C_{0sp}$	21.5	1.5	-	37.1	3.3	34.4	44.0	4.3	37.4	51.6	4.5	38.9	57.0	4.5	42.0	1.77E+02	1.23E+03
24	M10sp	$FA_{0}F_{0}C_{100sp}$	59.9	4.1	-	63.0	5.2	43.5	66.0	5.4	46.7	71.2	5.5	47.6	73.0	5.4	47.7	3.32E+02	1.54E+03
25	M12sp	$FA_{0}F_{100}C_{100sp}$	47.1	3.1	-	49.0	3.7	33.9	57.9	4.2	34.3	58.3	4.3	35.3	60.6	4.2	35.8	3.31E+02	1.53E+03
26	M14sp	$FA_{30}F_{50}$	39.5	2.7	-	53.8	3.8	38.3	57.5	4.1	41.5	69.4	4.2	42.9	74.0	4.1	44.0	2.38E+02	1.16E+03
27	M16sp	$FA_{60}F_{0}C_{100sp}$	22.5	1.8	-	38.0	3.5	38.3	45.2	4.4	41.7	56.6	4.5	43.2	59.0	4.5	43.6	1.46E+02	7.93E+02
28	M18sp	$FA_{60}F_{100}C_{100sp}$	18.5	1.5	-	32.3	2.6	30.1	44.3	3.6	31.5	51.3	3.6	32.8	54.0	3.6	35.5	1.45E+02	7.89E+02

[a] FA, F, C and SP are FA, FRA, CRA and SP, simultaneously, and the values stand for their incorporation level in concrete;
[b] Experimental data presented for the first time

3.1 Compressive strength

The f_{cm} of concrete containing both RA (fine and coarse) and FA has been studied extensively by the authors of this study [17] and other studies (Table 4). Hence, the influence of RA and FA on concrete is briefly shown. In fact, the f_{cm} of concrete is provided in order to be a benchmark (basis for comparison) for the other concrete characteristics, namely f_{ctm} and E_{cm}. In other words, the results of f_{ctm} and E_{cm} may not be properly explained without knowing the f_{cm}.

Table 4 shows the individual and combined effects of the incorporation of RA (0%, 25-40%, 50-60% and 80-100%) and FA (0, 15-20%, 30-45% and 50-60%) based on previous studies [34-45].

Table 4 - Effect of both FA and RA on the f_{cm} of concrete

Sources	Ages	Ref.	$f_{cm,cube}$ - reference concrete / $f_{cm,cube}$- materials														
RA (%)		(MPa)	0			25-40				50-60				80-100			
FA (%)			15-20	30-45	50-60	0	15-20	30-45	50-60	0	15-20	30-45	50-60	0	15-20	30-45	50-60
[34] F	7d	42	1.00	0.88	-	0.98	0.86	0.81	-	0.90	0.87	0.88	-	0.81	0.76	0.76	-
	28d	55	0.96	0.78	-	0.91	0.97	0.78	-	0.89	0.85	0.80	-	0.80	0.76	0.67	-
	56d	55	1.00	0.91	-	1.09	1.05	0.99	-	0.91	0.87	0.85	-	0.97	0.85	0.78	-
[35] F	28d	47	-	-	-	0.82	1.17	0.77	-	0.78	-		-	0.46	-	-	-
[36] F	7d	41	-	-	-	1.06	-	0.59	-	1.06	-	0.65	-	0.90	-	-	-
	28d	52	-	-	-	1.02	-	0.63	-	1.06	-	0.67	-	0.87	-	-	-
	56d	59	-	-	-	0.98	-	1.01	-	0.99	-	1.02	-	0.84	-	-	-
[37] C	28d	51	-	-	-	-	-	-	-		-	-	-	0.90	-	0.70	-
[38] C	7d	30	0.50	-	-	1.00	0.60	-	-		-	-	-	0.90	0.60	-	-
	28d	31	0.90	-	-	1.00	0.90	-	-		-	-	-	0.90	0.70	-	-
	90d	35	1.00	-	-	0.90	0.80	-	-		-	-	-	0.80	0.70	-	-
[39] C	7d	20	-	0.90	-	1.00	-	1.00	-	0.90	-	1.00	-	1.10	-	1.00	-
	28d	26	-	1.20	-	1.00	-	1.20	-	1.00	-	1.10	-	1.00	-	1.10	-
	56d	28	-	1.30	-	0.90	-	1.20	-	1.00	-	1.10	-	-7.00	-	1.10	-
	90d	31	-	1.30	-	1.00	-	1.20	-	1.00	-	1.10	-	0.90	-	1.10	-
	180d	33	-	1.40	-	1.00	-	1.30	-	1.00	-	1.20	-	0.90	-	1.20	-
	356d	36	-	1.40	-	1.00	-	1.40	-	1.00	-	1.30	-	0.90	-	1.20	-
[40] C	7d	20	-	-	-	-	-	-	-	-	-	-	-	-	1.00	0.90	0.80
	28d	25	-	-	-	-	-	-	-	-	-	-	-	-	1.00	0.90	0.80
	56d	33	-	-	-	-	-	-	-	-	-	-	-	-	1.00	0.90	0.80
	90d	37	-	-	-	-	-	-	-	-	-	-	-	-	1.00	0.90	0.80

[41][C]	7d	33	-	-	-	-	-	-	-	-	-	-	-	0.94	0.88	0.76	0.64
	28d	47	-	-	-	-	-	-	-	-	-	-	-	0.94	0.91	0.88	0.85
	91d	52	-	-	-	-	-	-	-	-	-	-	-	0.96	1.02	1.00	0.88
[41][F&C]	7d	25	-	-	-	-	-	-	-	-	-	-	-	0.76	0.64	0.58	0.48
	28d	37	-	-	-	-	-	-	-	-	-	-	-	0.79	0.69	0.66	0.62
	91d	40	-	-	-	-	-	-	-	-	-	-	-	0.77	0.73	0.71	0.69
[42][e F&C]	28d	49	0.90	0.80	0.70	-	-	-	-	0.90	0.90	0.80	0.70	0.80	0.80	0.70	0.60
	1y	57	1.10	0.90	0.90	-	-	-	-	0.90	1.00	0.80	0.80	0.80	0.90	0.80	0.60
	3y	61	1.10	1.00	1.00	-	-	-	-	0.90	1.00	0.90	0.90	0.80	0.90	0.90	0.70
	5y	64	1.10	1.00	1.00	-	-	-	-	1.00	1.00	1.00	0.90	0.90	0.90	0.90	0.80
	10y	68	1.10	1.00	1.00	-	-	-	-	1.00	1.00	1.00	0.90	0.90	1.00	1.00	0.80
[43][F&C]	7d	23	-	0.80	0.80	0.80	-	0.70	0.70	0.80	-	0.70	0.70	0.70	-	0.70	0.60
	14d	30	-	0.90	0.80	0.80	-	0.80	0.70	0.70	-	0.70	0.70	0.60	-	0.60	0.60
	28d	54	-	0.70	0.60	0.80	-	0.60	0.60	0.70	-	0.50	0.50	0.60	-	0.50	0.50
	56d	57	-	0.70	0.60	0.80	-	0.70	0.60	0.70	-	0.60	0.50	0.60	-	0.60	0.50
[44][e F&C]	7d	25	1.00	0.80	0.30	-	0.90	0.90	0.50	-	0.60	0.50	0.30	-	-	0.30	0.20
	28d	34	1.10	1.20	1.00	-	1.00	1.10	0.90	-	0.80	0.80	0.80	-	-	0.60	0.50
	56d	39	0.00	1.50	1.30	-	1.00	1.20	1.00	-	0.80	1.10	1.00	-	-	0.70	0.60
	90d	39	1.10	1.40	1.40	-	0.90	1.40	1.10	-	0.90	1.00	1.00	-	-	0.80	0.70
[45][e F&C]	28d	29	-	-	1.10	-	-	-	-	-	-	-	-	1.20	-	-	1.10

[F and C] Mixtures with simultaneous incorporation of FRA and CRA. [e] FA incorporated as an additional binder (cement was not substituted)

They show that, by incorporating 20-30% of both FA and CRA, the f_{cm} of concrete may be higher than that of an equivalent traditional mix. For higher replacement levels (20-30%) of FA and CRA with cement and virgin gravels, f_{cm} linearly decreases with increasing amount of CRA and FA in concrete. In addition, according to the results of this study (experimental) and most results of the other studies, the use of FRA in concrete is more detrimental than that of the CRA. Similarly to RA, FA is detrimental to the f_{cm} of concrete. However, according to previous studies [11, 46-53], the f_{cm} of concrete containing up to 40% of FA at ≈ one month are similar to or lower than that of the reference concrete at ≈ three months. Apart from the fact that the high amount of FA and RA is harmful to the f_{cm} of concrete, it is still better (advisable) to simultaneously incorporate RA and FA in concrete rather than just one of them, because after a certain time (e.g. one month) the "strength-development" of mixtures containing both FA and RA is much better than that of the mixtures with either RA or FA. A possible explanation for these results may be the pozzolanic reaction between the FA (rich with silicon dioxide) and RA (rich with calcium hydroxide) [42]. Further details related to the combined effects of both FA and RA were shown in other studies [17, 54].

3.2 Splitting tensile strength

The tensile strength of concrete was determined indirectly through splitting tensile strength. The test was performed according to standard EN 12390-6 almost at 0.2, 1, 3, 6 and 12 months (Table 3).

3.2.1 Influence of FRA on the f_{ctm}

Figure 2 presents the development of f_{ctm} (splitting tensile strength) at 0.2-12 months for concrete mixtures containing various quantities of FRA. The strength of the concrete mixtures decreased with increasing quantities of FRA. Concrete mixtures with "50% and 100%" of FRA obtained lower f_{ctm} by 11.5% and 19.3% at ≈ one month, and 10.2% and 15.5% at ≈ 12 months, respectively. This decrement was mainly due to the additional water required to increase the w/b in RA concrete mixtures to reach the target slump.

Similarly to f_{cm}, the f_{ctm} of concrete mixtures increased over time. However, the development rate of f_{ctm} compared to the corresponding f_{cm} is less significant. For example, the ratio "$f_{ctm,\ (other\ curing\ ages)}/f_{ctm\ (28\ days)}$" was "88%, 109%, 110% and 111%" with the use of NA, and "79%, 108%, 111% and 112%" when 50% of natural sand was substituted with FRA, and "80%, 106%, 112% and 116%" when 100% of natural sand was substituted with FRA at "0.2, 3, 6 and 12 months", respectively. The differences between traditional concrete and FRA concrete decreased at longer ages. For example, after ≈ three months, the ratio "f_{ctm} (t)/f_{ctm} (28 days)" increased with increasing quantities of FRA. Thus, this study confirms that, after 3 months, the strength development rate of the FRA concrete is higher than that of the mixtures with traditional materials. This behavior was related to the high quantity of "non-hydrated old cement" particles in FRA and the characteristics of binder considered to make parent concrete (further comments on this phenomena have been made in study [17] for the f_{cm} of the RA concrete). As shown in Figure 3, the results of this study agreed with previous studies [36, 55-59].

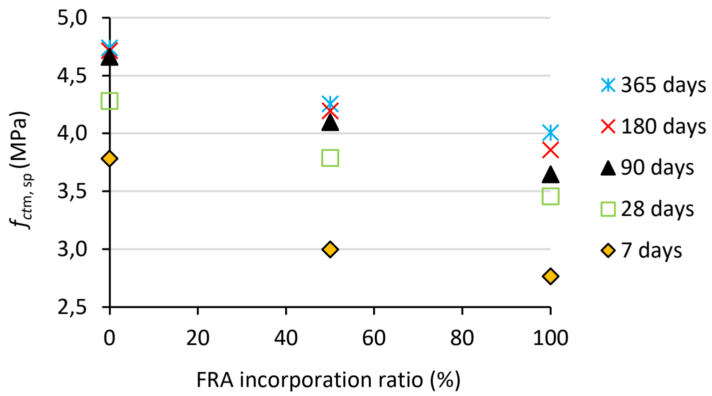


Figure 2 - Effect of the FRA quantities on the f_{ctm} of concrete at 0.2-12 months

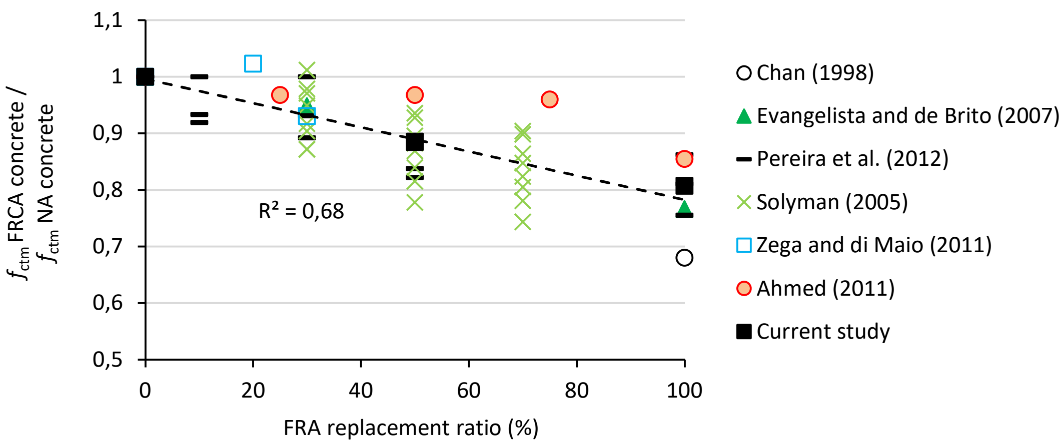


Figure 3 - Influence of increasing FRA on the f_{ctm} of concrete at ≈one month

3.2.2 Influence of CRA on the splitting tensile strength of concrete

Figure 4 shows the effect of 100% replacement of natural gravel with CRA on the f_{ctm} of concrete mixtures at 0.2-12 months. The figure shows that the f_{ctm} decreased 10.2%, 1.4%, 1.4%, 1.1% and 1.4% for full CRA content at ≈ 0.2, 1, 3, 6 and 12 months, respectively. The figure shows that the reduction of f_{ctm} between concrete with traditional materials and CRA slightly decreased at longer ages due to the high quantity of non-hydrated old cement particles in CRA (further comments on this phenomena have been made in study [17] for the f_{cm} of the RA concrete). Furthermore, the incorporation of FRA is less harmful than that of FRA because CRA absorbs less water (5%) than FRA (8%). As for f_{cm}, since the adhered mortar (its strength may be lower than new cement paste) in CRA is lower than in FRA, the f_{ctm} of concrete does not significantly decrease with CRA incorporation. As for FRA concrete (§3.2.1), the strength development accelerated with the incorporation of CRA. However, due to the difference between the quantities of non-hydrated cement particles in FRA and CRA [60], after one month, the f_{ctm} development rate of the concrete mixtures containing FRA is higher than CRA. As shown in Figure 5, the results of this study agree with those of previous ones [6, 61-70]. However, a few researches show that CRA concrete exhibited greater or similar f_{ctm}. This is because they added extra cement to RA concrete.

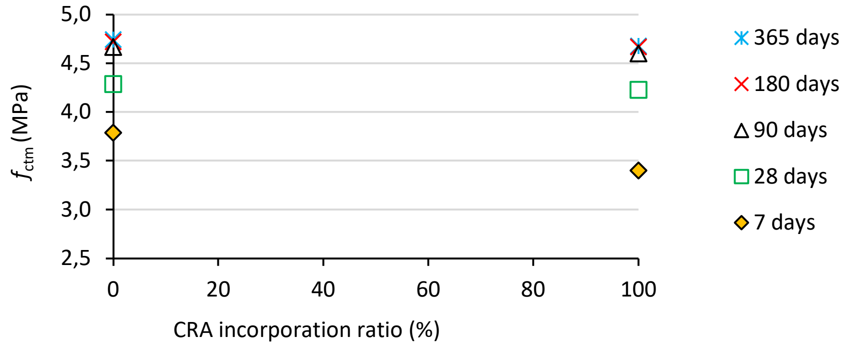


Figure 4 - Effect of the FRA quantities on the concrete f_{ctm} at 0.2-12 months

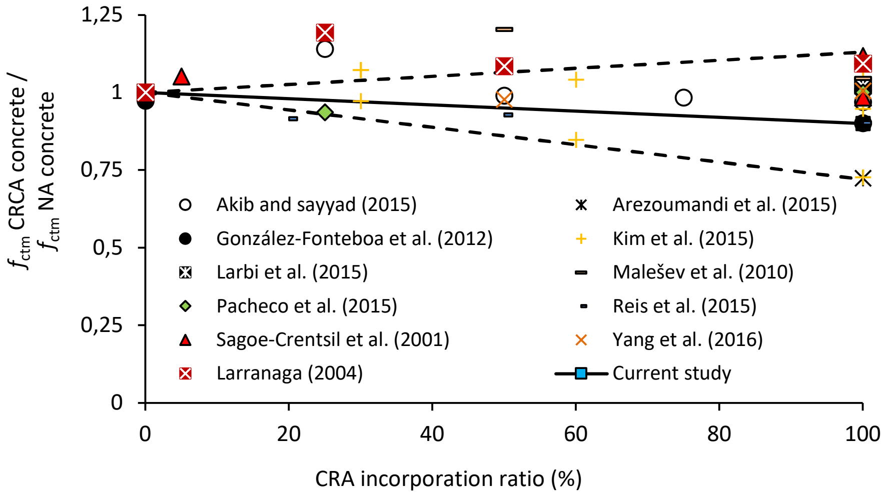


Figure 5 - Influence of incorporating FRA on the relative f_{ctm} of concrete at 28 days (dash line - upper and lower boundaries for 95% confidence interval)

3.2.3 Combined effect of CRA and FRA on the splitting tensile strength of concrete

Similarly to individual effects of incorporating FRA (§3.2.1) or CRA (§3.2.2), the f_{ctm} of concrete mixtures decreased with increasing quantities of FRA and CRA. In addition, after ≈one month, the f_{ctm} development rate of mixtures with both FRA and CRA (Figure 6) was higher than that of the mixtures with FRA (Figure 2) or CRA (Figure 4) at older ages. This is due to the presence of a higher quantity of non-hydrated cement particles. Thus, the results confirmed that the f_{ctm} development rate of concrete mixture increases with increasing incorporation of RA especially when 100% of natural sand and gravel with FRA and CRA.

Figure 7 shows that the results of this study agree with the trend of previous studies [71-74], and it shows that the difference between the line of equality and the trend of the mixtures increases with increasing strength of the concrete mixtures. This can be explained by the difference between the strength of the new cement pastes and the old adhered mortar attached to the RA.

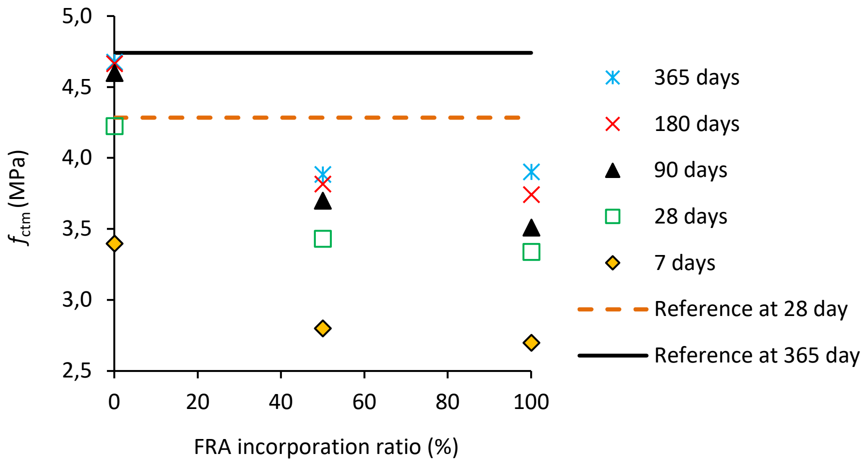


Figure 6 - Effect of the FRA quantities on f_{ctm} of CRA concrete at 0.2-12 months

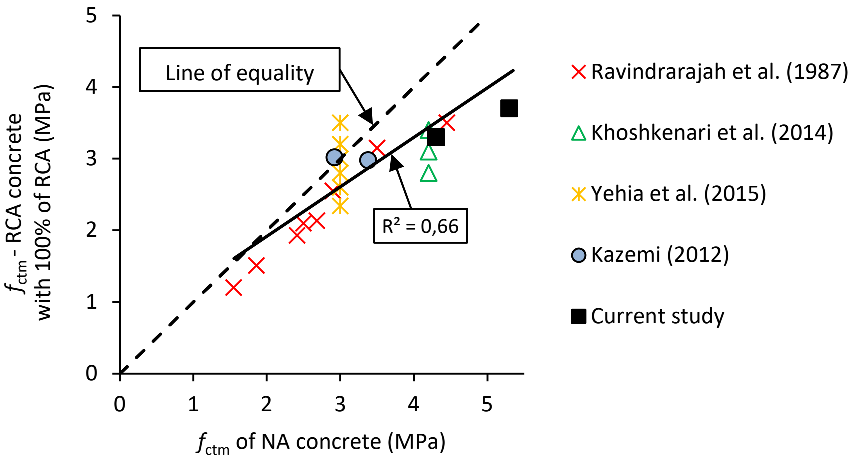


Figure 7 - Effect of 100% replacement of NA with RA on the f_{ctm} at 28 days

3.2.4 Effect of FA on the splitting tensile strength of concrete

As for f_{cm}, the use of FA in concrete mixtures is harmful regarding f_{ctm}, namely at early ages. The f_{ctm} of concrete mixtures decreased “57.2% and 70.9%” at ≈0.2 month, “29.3% and 47.2%” at ≈ one month, “10.0% and 28.6%” at ≈ three months, “8.3% and 27.0%” at ≈ six months, and “4.69% and 23.4%” at ≈ twelve months, when “30% and 60%” of cement was substituted with FA, respectively (Figure 8). Since the pozzolanic reaction of FA is lower [75], the difference between the f_{ctm} of concrete containing FA and traditional materials decreases over time . After three months, the f_{ctm} of concrete is slightly affected when 30% of cement substituted with FA. As recommended by European standard [76], it is not allowed to replace more than 55% cement with FA. For example, the results show that f_{ctm} significantly decreased with the use of 60% of FA, namely at early ages. This finding was also reported by other studies [38, 42, 45, 77-79]. This is due to the fact that, for high quantities of FA in concrete, most of the FA particles do not behave as binder, in fact they work as filler. Moreover, this study shows that after ≈ three months the f_{ctm} development of FA concrete slows down. A similar conclusion was reached by other studies [80, 81].

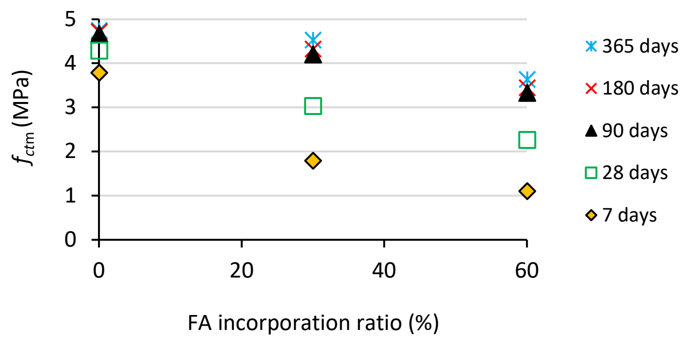


Figure 8 - Effect of the FA use on concrete’s f_{ctm} at 0.2-12 months

3.2.5 Combined influence of RA and FA on the splitting tensile strength of concrete

As for f_{cm}, the results of this study show that, in terms of f_{ctm}, FA can be favorable in concrete containing RA (Table 3). For example, for concrete mixtures without CRA, using low contents of FA and “0%, 50% and 100%” of FRA resulted in lower f_{ctm} by “52.7%, 61.2% and 63%” at ≈0.2 months, “29.3%, 32.3% and 38.4%” at ≈ one month, “10%, 16.4% and 22.8%” at ≈ three months, “8.3%, 11.2% and 19.2%” at ≈ six months, and “4.6%, 4.7% and 13.3%” at ≈ twelve months, respectively. Similar trends can be seen when incorporating 60% of FA and different incorporation levels of FRA, especially at early ages, but, for ages exceeding ≈ three months, the f_{ctm} of concrete produced with high quantities of FA was lower than that made with both FA and RA. This can be related to the pozzolanic reaction between RA and FA (further comments on these phenomena has been made in study [17] for the f_{cm} of the RA concrete).

For concrete mixtures with high quantities of CRA (100%), using 30% of FA and “0%, 50% and 100%” of FRA caused f_{ctm} decrements of “57.8%, 61.4% and 64.3%” at ≈0.2 months, “31.5%, 42.8% and 44%” at ≈ one month, “17.2%, 31.8% and 33.5%” at ≈ three months, “10.9%, 24.6% and 26%” at ≈ six months, and

"3.6%, 16% and 16.8%" at ≈ twelve months, respectively. Similar trends are seen when incorporating 60% of FA, 100% of FRA, and different incorporation levels of FRA, especially at early ages. However, after 7 days, the strength of concrete made with incorporation levels of 50% FRA is lower than that of the mixtures containing 100% of FRA when both mixtures contain 60% FA and 100% FRA (Table 3). This is due to the fact that when a high quantity of FA is incorporated in the mixture, the strength of the binder paste significantly decreased. Therefore, failure occurred in the relatively weaker binder paste rather than in the old adhered mortar. Thus, for low strength concrete, incorporating a high volumes of FRA may not considerably influence the ultimate strength of the mixtures; in fact, it increases the strength of the binder paste by providing calcium hydroxide to the silicon dioxide of FA to from C-S-H. A similar conclusion was reached by studies [38, 42, 45, 77-79] for the concrete mixtures containing various quantities of both "FA and CRA" (Figure 9), or for mixtures containing "FA and FRA" [36, 82], or "FA and both FRA and CRA" [43, 44, 79].

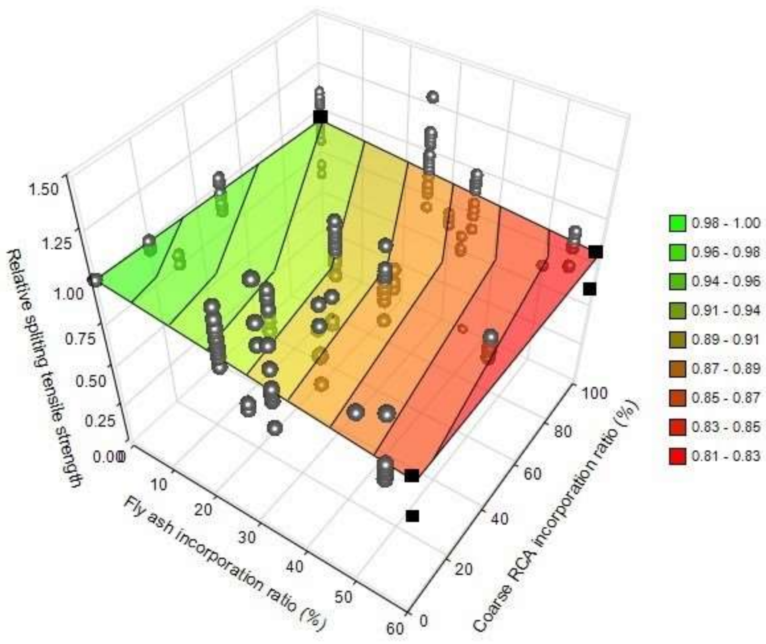
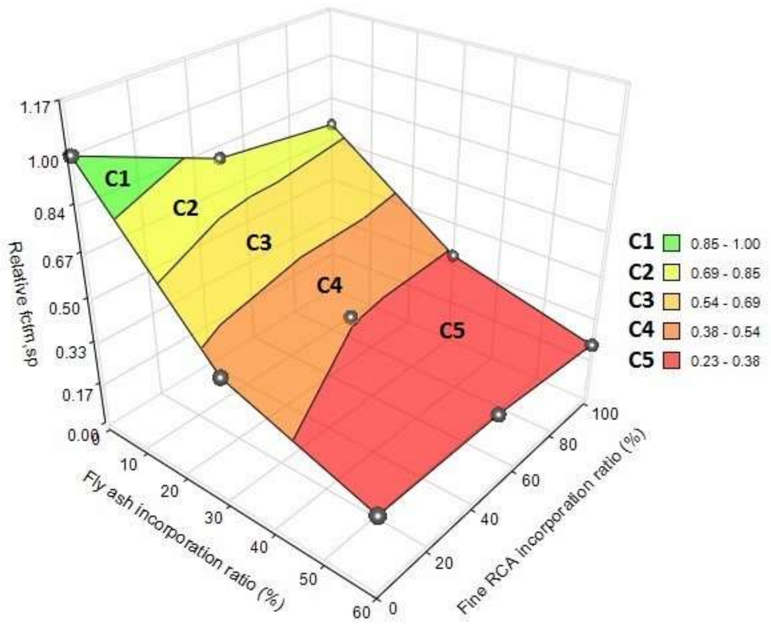
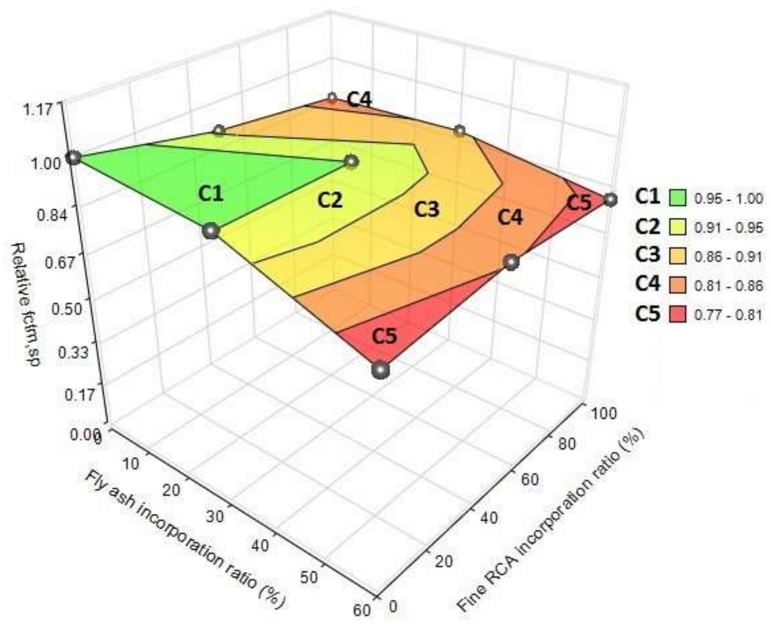


Figure 9 - Effect of replacing cement and gravel with FA and CRA, respectively on the f_{ctm} of concrete, at different curing ages. (Black circle and square are relative results based on previous studies and the present study, respectively)

Broadly speaking, the results show that f_{ctm} reduces with increasing quantities of FA and/or FRA. However, the percentages of reduction at early ages were significantly higher than those at older ages. For example, the percentages of reduction of mixtures M1-M9 at ≈ one month (Figure 10a) were significantly higher than those at ≈ twelve months (Figure 10b).



(a)



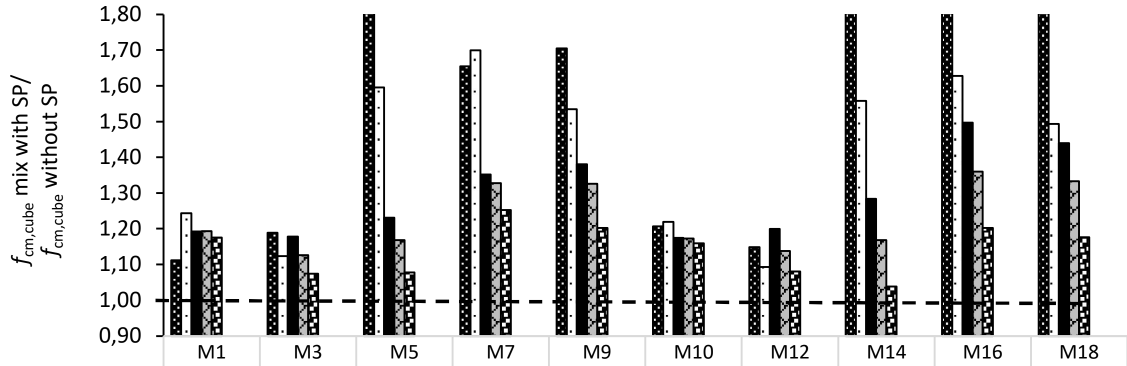
(b)

Figure 10 - Effect of FA and FRA use on concrete's f_{ctm} at ≈ (a) 1 and (b) 12 months

3.2.6 Influence of w/b on the splitting tensile strength of concrete mixtures

The use of SP increases the f_{ctm} of concrete mixtures due to fact that less water is needed to maintain the target workability and disperse the cement particles [28, 83, 84]. The strength of concrete mixtures with SP (M1sp:M18sp) was between 1.5-4.2 MPa at ≈0.2 month, 2.6-5.3 MPa at ≈ one month, and 3.6-5.6 MPa at ≈ three months, 3.6-5.6 MPa at ≈ six months, and 3.6-5.6 MPa at ≈ twelve months (Table 3).

Figure 11 shows the relative f_{ctm} of the same mixtures with and without SP. Similarly to f_{cm} [17], SP appeared to be more sensitive in FRA concrete because of the higher surface area of FRA compared to natural sand. A similar conclusion was reached by other studies [57, 85]. Relative to FRA concrete, SP is less sensitive in CRA concrete because the total aggregates' surface area increases more with the incorporation of FRA than with that of CRA and, as a consequence, the particles of FRA disperse less relatively to the CRA particles. In contrast with RA, the performance of FA significantly increases with the use of SP because it helps the particles of FA to uniformly disperse in the mixture. Due to this reason, it is advisable to use SP in FA concrete, especially when RA is used because it helps the particles of FA to consume more calcium hydroxide from RA particles and obtain further C-S-H at early ages. Thus, it can be said that SP is less effective at older ages than at early ages.



	M1	M3	M5	M7	M9	M10	M12	M14	M16	M18
7 days	1,11	1,19	2,22	1,65	1,70	1,21	1,15	1,85	2,29	2,14
28 days	1,24	1,12	1,60	1,70	1,53	1,22	1,09	1,56	1,63	1,49
90 days	1,19	1,18	1,23	1,35	1,38	1,17	1,20	1,28	1,50	1,44
180 days	1,19	1,13	1,17	1,33	1,33	1,17	1,14	1,17	1,36	1,33
365 days	1,18	1,07	1,08	1,25	1,20	1,16	1,08	1,04	1,20	1,18
Fine RCA (%)	0	100	50	0	100	0	100	50	0	100
Coarse RCA (%)	0	0	0	0	0	100	100	100	100	100
Fly ash (%)	0	0	30	60	60	0	0	30	60	60

Figure 11 - Effect of SP on the f_{ctm} of concrete mixtures

3.2.7 Relationship between the splitting tensile strength and other concrete properties

Figure 12 shows that there is a strong relationship between f_{cm} and f_{ctm}. Generally, the average regression line for all mixtures is adapted from the regression line proposed by Eurocode 2 [86]. However, some scatter in the results can be seen because in the experimental campaign, the concrete mixtures were made with different incorporation levels of non-conventional materials, namely FA, RA, and SP, replacing conventional materials, namely cement and NA considered in the standard. Similarly to the regression line proposed in Eurocode 2, a power regression function was considered with coefficient of determination R^2 equal to 0.86. This is because the brittleness of concrete increases as its strength increases [87].

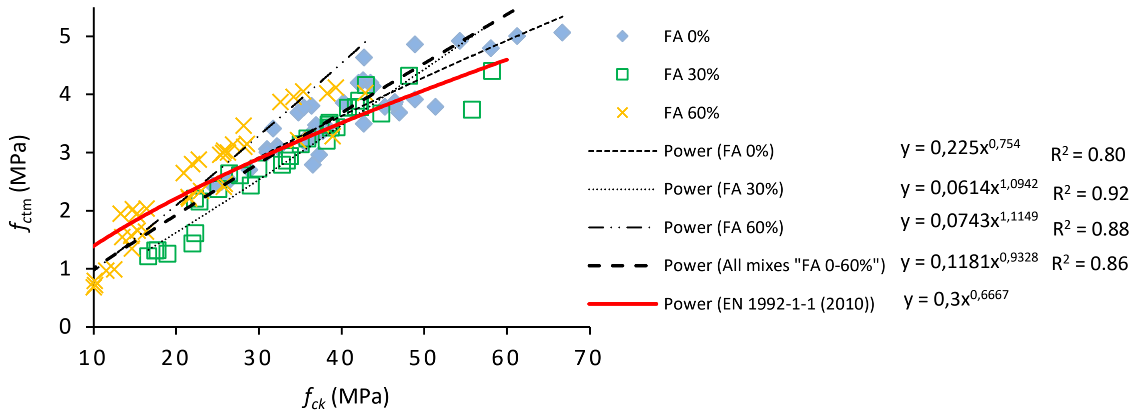


Figure 12 - Relationship between the f_{ctm} and f_{cm} of concrete with increasing use of FA and/or RA, with and without SP, at ≈0.2, 1, 3, 6 and 12 months

3.3 Modulus of elasticity

The E_{cm} of concrete is a stress to strain ratio at whatever curing condition and age, and it depends on several factors [88, 89], mainly the aggregate [90]. Generally, there are three methods to calculate the elastic modulus of concrete, namely, initial tangent, tangent and secant modulus. The secant modulus is the most widely used method because it represents the real deformation at a specific point and it is more precise to determine. In this study, the secant modulus was determined for all concrete mixtures at ≈0.2, 1, 3, 6 and 12 months (Table 3).

3.3.1 Influence of FRA on the modulus of elasticity of concrete

The E_{cm} of the concrete mixtures decreased with the incorporation ratio of FRA. The concrete mixtures with 50% and 100% of FRA obtained lower modulus by 11.0% and 20.8% at ≈ one month, 13.3% and 19.5% at ≈ three months, 12.3% and 17.3% at ≈ three months, and 12.0% and 16.9% at ≈ twelve months, respectively (Figure 13a). Two main factors can explain these decrements. First, E_{cm} mainly depends on the cement paste and aggregates, particularly on their nature, as well as their arrangement and bond [91]. Relatively to NA, RA is less stiff because of the presence of the attached cement mortar, which has higher deformability than that of the NA “stone” [88]. Therefore, with increasing use of RA, the presence of attached mortar increased and, consequently, the modulus of elasticity decreased. Secondly, due to its shape and high porosity, RA needs additional water to maintain the target slump [28]. This affects the stiffness of the binder paste, its porosity and the bond between RA and binder paste (ITZ), which directly affect the E_{cm} of concrete [92]. As shown in Figure 13b, similar conclusions were drawn in previous studies [56, 58, 60, 93]. Moreover, the difference between the E_{cm} of concrete containing RA and NA decreased over time. A possible explanation for this may be the type of cement in the source concrete used to produce RA [17, 28], because this cement contains FA that requires more time to produce high amounts of hydration products and obtain the final strength of RA, namely in the attached mortar itself and in the ITZ between stone (NA) and the attached mortar.

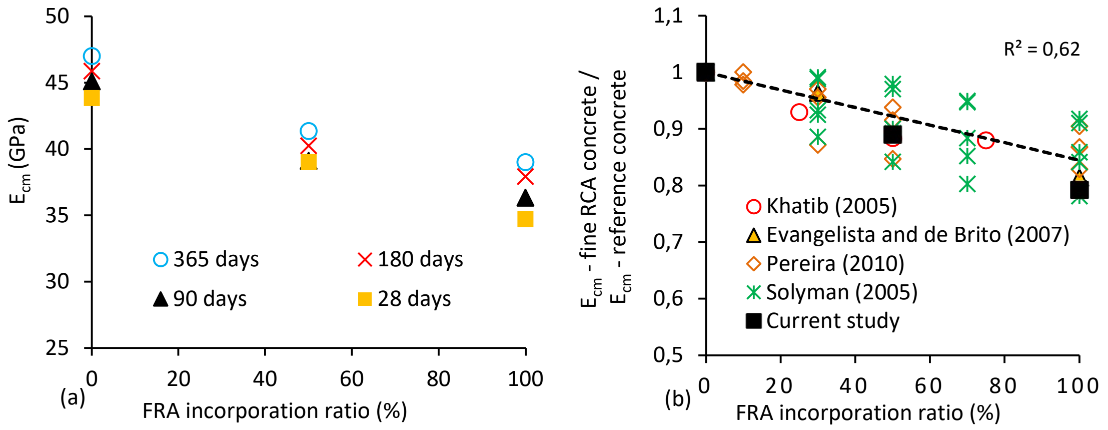


Figure 13 - Effect of FRA use on the E_{cm} of concrete (a) over time (present study) and (b) at 28 days (present and previous studies)

3.3.2 Influence of CRA on the modulus of elasticity of concrete

Generally, in concrete, the volume of CRA is higher than that of FRA, but the incorporation of FRA is more detrimental than that of CRA. This can be explained by the presence of attached mortar that is the main contributor to the reduction of stiffness of concrete, and which quantity is lower in CRA than in FRA [35]. Since the attached mortar absorbs lots of water, CRA concrete required less water than FRA concrete to have the target slump, which directly affected the density of the cement paste and, consequently, the modulus of elasticity. The results show that E_{cm} decreased 15.4%, 13.5%, 11.9% and 11.9% with the incorporation of 100% CRA at ≈1,3, 6, and 12 months, respectively (Figure 14a). Moreover, the results of previous studies [6, 63, 65-68, 94-96] are coherent with this one (Figure 14b). In addition, after ≈one month, the E_{cm} development rate of concrete mixtures containing CRA was smaller than in mixtures made with FRA. This is due to the high non-hydrated old cement particles in FRA composition compared to CRA.

3.3.3 Combined influence of fine and FRA on the modulus of elasticity of concrete

As shown in Figure 15, the results obtained for the combined effect of FRA and CRA confirmed that the E_{cm} of concrete mixtures reduced with increasing quantities of RA. It also confirmed that, after ≈ one months, the E_{cm} development rate of concrete increased with increasing incorporation levels of RA. A similar conclusion was reached in another study [71]. In addition, the E_{cm} of concrete mixtures reduced by about 25.9%, 24.8%, 22.9% and 22.8% when 100% of natural gravel was substituted with CRA and 50% of FRA was introduced, and decreased 36.0%, 35.5%, 33.4% and 33.1% when natural sand and gravel were fully substituted with FRA and CRA, at ≈0.2, 1, 3, 6 and 12 months, respectively (Figure 15).

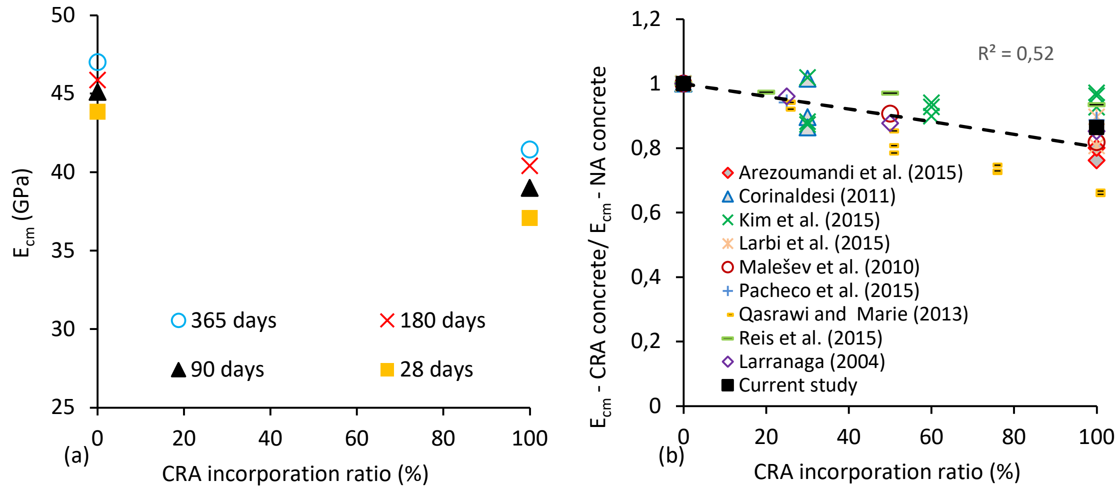


Figure 14 - Effect of CRA use on the E_{cm} of concrete (a) with time (present study) and (b) at 28 days (present and previous studies)

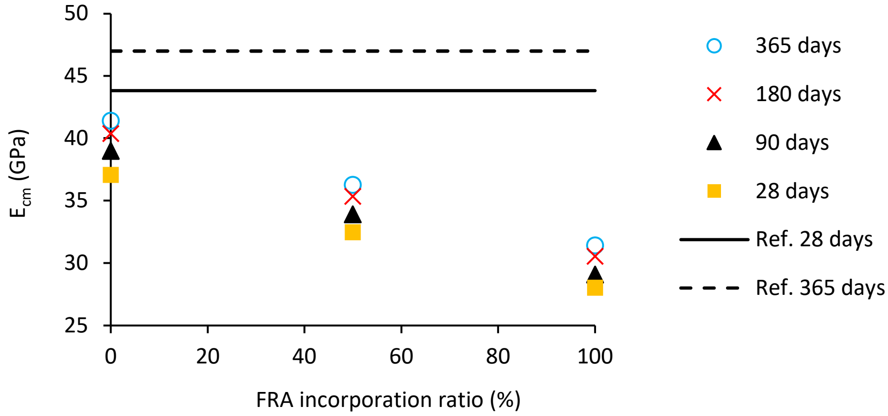


Figure 15 - Effect of FRA use on the E_{cm} of CRA concrete at 0.2-12 months

3.3.4 The Influence of FA on the modulus of elasticity of concrete

As expected, FA affected the E_{cm} of concrete less than RA. Up to ≈ one month, FA is detrimental to the E_{cm} of concrete (Figure 16a). As shown in Figure 16b, a similar conclusion was reached in other studies [46, 52, 81, 97, 98]. This is due to the low rate of the pozzolanic reactions of FA [75] and the fact that only a few particles of FA participate in the reaction [99]. At ≈three months, it increased 3% when a low quantity of FA was incorporated and decreased 7% when a high quantity was incorporated. At later ages, it increased significantly when a low quantity of FA was incorporated and slightly decreased for high incorporation levels of FA.

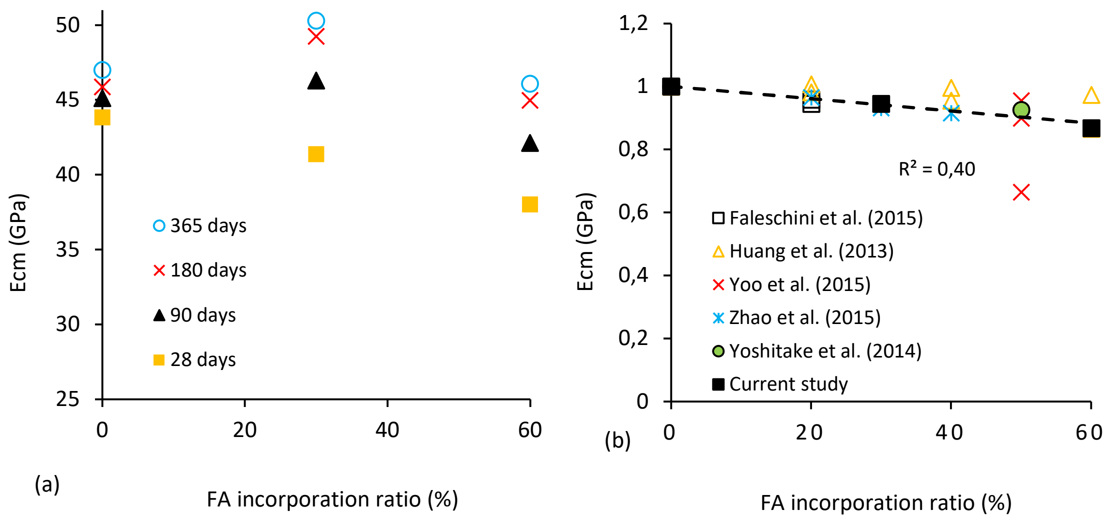


Figure 16 - Effect of FA use on the E_{cm} of concrete (a) with time (present study) and (b) at 28 days (present and previous studies)

Broadly speaking, after three months, E_{cm} improves by introducing low quantities of FA and it seems not to be affected by high contents of FA. A similar conclusion was reached on other studies [52, 97]. These phenomena are related to the explanations mentioned for f_{ctm} (§3.2.4) and f_{cm} [17], namely, for a low incorporation ratio of FA, most of its particles react as an active binder rather than a filler and also decrease the required water to obtain the target slump. Thus, the two mentioned factors directly affect the density of the binder paste and consequently E_{cm}. For a high quantity of FA, less water is needed to reach the target workability and it may improve E_{cm}, but most of the FA particles exceeding the standard limit acted as filler rather than pozzolanic binder, which offset the previous effect.

3.3.5 Combined influence of RA and FA on the modulus of elasticity of concrete

The E_{cm} of concrete decreased with increasing quantities of RA but, for incorporation ratios of FA with RA either individually of jointly, E_{cm} depends on the quantities of FA and the age of the concrete mixtures (Table 3). As shown in Figure 17, a similar conclusion was reached in other studies [37, 39, 42, 77].

For all mixtures, the E_{cm} of RA concrete either with or without FA is lower than that of the traditional concrete at every age. Nevertheless, when FA is used in RA concrete, the sum of the decrements as a result of the single influence of RA and FA is bigger than the real decrement of the mixtures produced with both FA and RA. The difference between the real decrement and the sum of the single effects of RA and FA significantly increased at later ages (Figure 18). This can be attributed to the same reason of the trends of other strength properties, namely the reaction between calcium hydroxide of RA and silicon dioxide of FA.

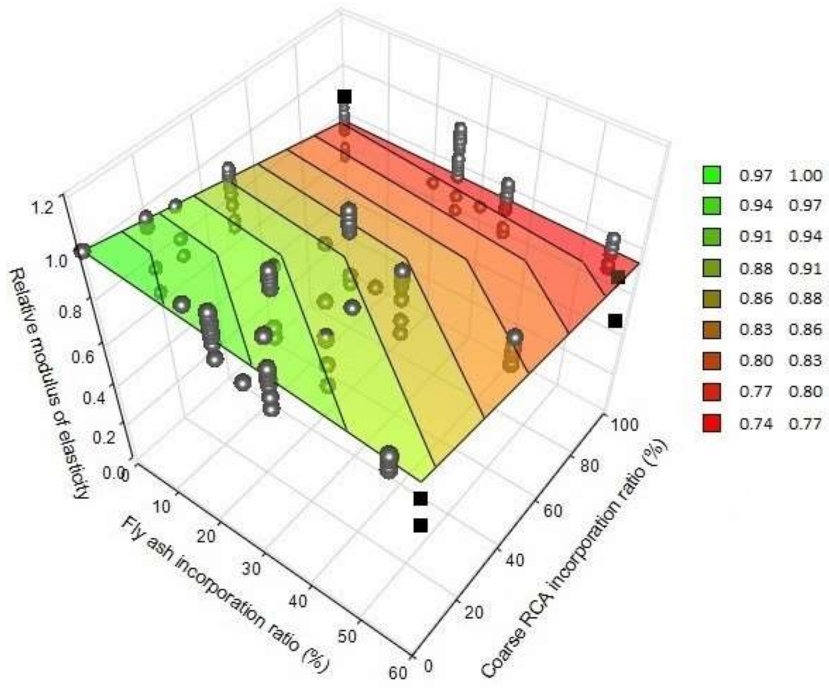
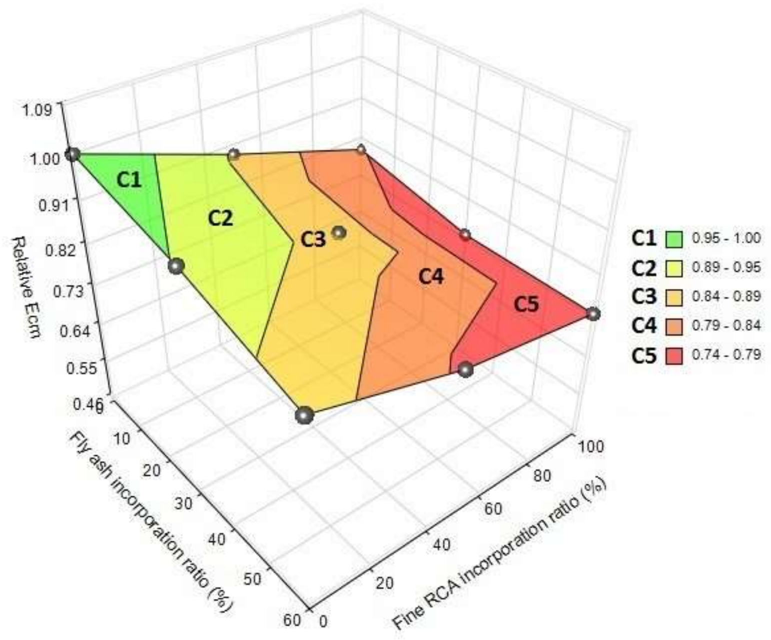
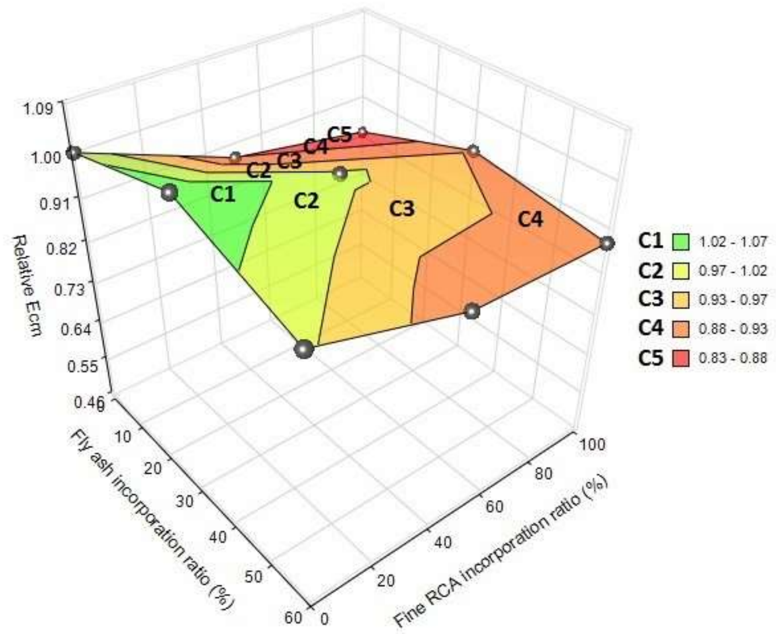


Figure 17 - Influence of FA and CRA use on the E_{cm} of concrete at 28 days and over. (Black circle and square are relative results based on previous studies and the present study, respectively)



(a)



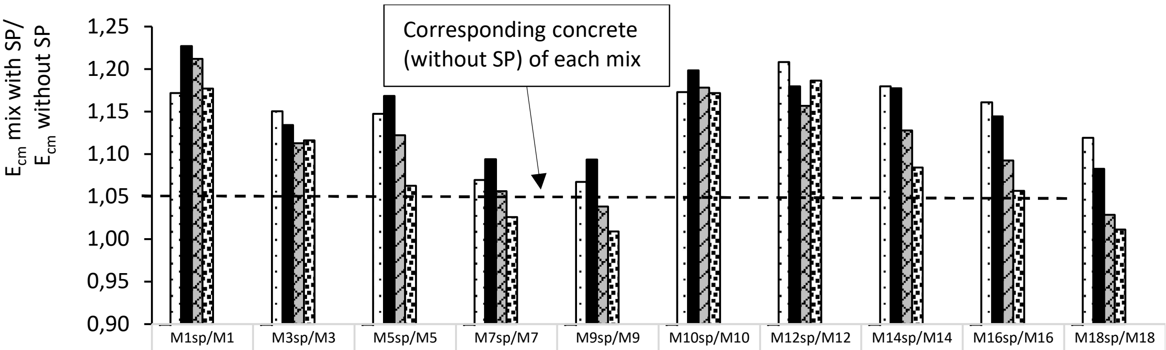
(b)

Figure 18 - Effect of FA and FRA use on the E_{cm} of concrete at ≈(a) 1 and (b) 12 months

3.3.6 Influence of w/b on the modulus of elasticity of concrete

Figure 19 shows the ratio between the E_{cm} of the same mixtures with SP and without SP. As expected, relative to f_{cm}, E_{cm} increased less with the use of SP (Figure 19). In fact, the efficiency of SP depends on the quantity and type of replacement materials used in concrete. The results show that E_{cm} depends more on the properties of the aggregates than on those of the cement paste.

The results show that the mixtures with SP appeared to be more sensitive to increasing incorporation levels of RA due to the same facts that explained the f_{cm} of concrete mixtures [17], namely the total specific surface of the aggregate increases as the quantity of RA increases. Contrary to expectations, given the trends found in other properties, relative to OPC concrete, this study found smaller improvements due to the use of SP on the E_{cm} of the FA mixtures, especially at later ages. This may be related to the fact that the E_{cm} of concrete is mainly affected by the characteristics of aggregates rather than by the binder paste. However, further study is required to confirm this phenomenon.



	M1sp/M1	M3sp/M3	M5sp/M5	M7sp/M7	M9sp/M9	M10sp/M10	M12sp/M12	M14sp/M14	M16sp/M16	M18sp/M18
7 days	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
28 days	1,17	1,15	1,15	1,07	1,07	1,17	1,21	1,18	1,16	1,12
90 days	1,23	1,13	1,17	1,09	1,09	1,20	1,18	1,18	1,14	1,08
180 days	1,21	1,11	1,12	1,06	1,04	1,18	1,16	1,13	1,09	1,03
365 days	1,18	1,12	1,06	1,03	1,01	1,17	1,19	1,08	1,06	1,01
Fine RCA (%)	0	100	50	0	100	0	100	50	0	100
Coarse RCA (%)	0	0	0	0	0	100	100	100	100	100
Fly ash (%)	0	0	30	60	60	0	0	30	60	60

Figure 19 - SP effects on the E_{cm} of concrete mixtures with and without RA and FA

3.3.7 Relationship between the modulus of elasticity and other concrete properties

In the present study, the experimental E_{cm} of mixtures was compared with the calculated E_{cm} resulting from the compressive strength of concrete mixtures at ≈1, 3, 6 and 12 months. For this purpose, the calculated modulus of elastic was determined by using models (Equation 1) suggested by Eurocode 2 (EN-1992-1-1, 2008). As shown in Figure 20, the regression line for all mixtures is adapted from the one proposed by Eurocode 2. The findings of this study suggest that the equation proposed by Eurocode 2 is acceptable for concrete mixtures produced with FA and/or RA, without and with SP, and there is a strong correlation between f_{cm} and E_{cm}.

$$E_{cm}(t) = ((f_{cm}(t)/f_{cm})^2) \cdot E_{cm} \quad (1)$$

Where E_{cm} is the modulus of elasticity at 28 days, f_{cm} the compressive strength at 28 days, $E_{cm}(t)$ and $f_{cm}\ (t)$ these values at t days. The $f_{cm}\ (t)$ value is determined from the experimental $f_{cm,cube}$ value according to [17].

Figure 21 shows that most of the concrete mixtures (about 99%) were above the Eurocode2 curve of concrete mixtures with sandstone aggregates, which means that there is a 99% chance that the E_{cm} of mixtures produced with FA and/or RA with known f_{cm} is above the Eurocode2 curve corresponding to sandstone aggregates. In general, it is concluded that E_{cm} was slightly underestimated by the normative expression when NA was used either with or without incorporation ratio of FA.

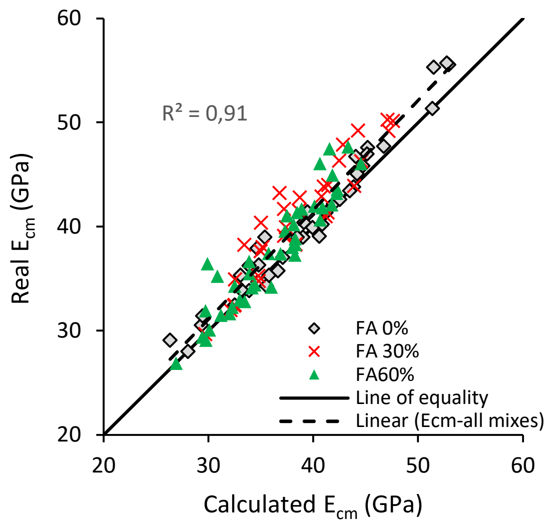


Figure 20 - Comparison between the experimental E_{cm} value and the E_{cm} value proposed by Eurocode 2

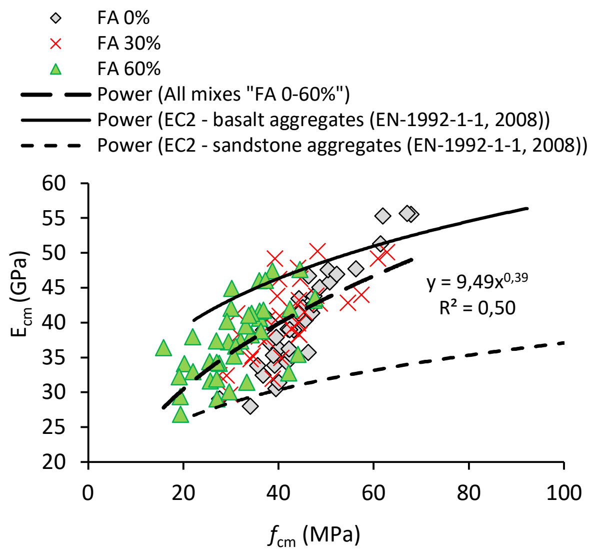


Figure 21 - Comparison between the relationship between E_{cm} and f_{cm} from the current study and those proposed by Eurocode2

Figure 22 shows that there is a strong correlation between the E_{cm} and f_{ctm} of RA mixtures without and with incorporation of 30% of FA (with coefficient of determination R^2 equal to 0.80 and 0.81, respectively). However, a poorer relationship (R^2 = 0.63) was found between them when incorporating 60% of FA in RA concrete. This discrepancy could be attributed to the fact that, for high quantities of FA, the mechanical strength of the mixtures dropped because a significant amount of FA particles act as a filler rather than as a pozzolanic binder, affecting the binder paste. For the modulus of elasticity, even though the stiffness of the paste is affected negatively by the FA particles acting as filler, the final result depends more on the aggregates than on the paste.

Figure 23 shows the correlation between the E_{cm} (Table 3) and the oven-dried density [100] of concrete mixtures with increasing quantities of FA and/or RA, without and with SP, at 0.2, 1, 3, 6, 12 months. The results show that there is a strong relationship between these two properties (R^2 between 0.88 and 0.94). This is because both the E_{cm} and the density of concrete mainly depend on the aggregate used. As explained before (§3.3.1), for E_{cm}, the stiffness of the aggregate is more important than that of the binder paste, since the aggregate occupies most of the volume of the mix. For the same reason, the aggregate is more responsible for the density of concrete than the binder paste [100].

3.4 Environmental impact

PE-NRe (non-renewable energy consumption) and GWP (potential global warming) are the most influential factors that need to be considered in the EI (environmental impacts) and resources use of any product [15]. Therefore, this study focuses on the influence of incorporation ratio of FA, FRA and CRA on the GWP and PE-NRe of the mixtures (Table 3). The results show that, apart from long transportation distances between the "FA suppler" and "concrete mixing plant", the "GWP and PE-NRe" of the concrete mixtures significantly decrease by replacing cement with FA. Contrary to FA, the transportation distances between the concrete plant and suppliers of "FRA, CRA and SP" are not long, but the "GWP and PE-NRe" are not significantly influenced by their incorporation ratios. The reasons behind changing the GWP and PE-NRe of the concrete mixtures are explained further in previous studies [16, 17]. Similar outputs can be found in previous studies, specifically the effect of FA [101-104] and RA [7, 105-108] on GWP, and FA [101, 104, 109] and RA [107, 109, 110] on the PE-NRe of concrete.

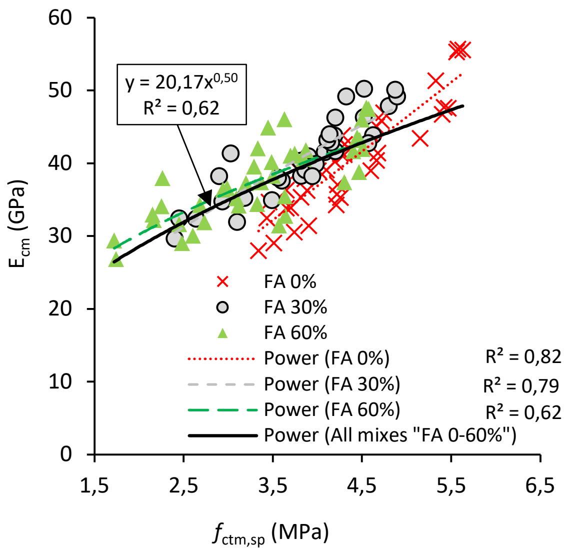


Figure 22 - Correlation between the E_{cm} and f_{ctm} of the concrete mixtures regardless of their age

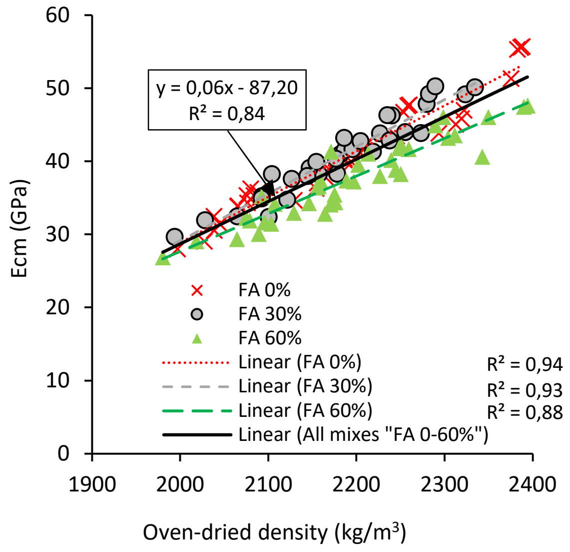


Figure 23 - Correlation between the E_{cm} and the oven-dried density of the concrete mixtures regardless of their age

Figures 24-25 show the effect of FA on the relationship between "f_{cm}, f_{ctm} and E_{cm}", and "GWP", and "Pe-NRe" of the concrete mixtures, respectively, regardless of the incorporation ratio of FRA and CRA. It seems that there are no clear relationships between "f_{cm}, f_{ctm} and E_{cm}", and GWP (Figure 24) or Pe-NRe (Figure 25) of the concrete mixtures. This means that the incorporation of each non-traditional material (e.g. FA, FRA, CRA and SP) differently affects each characteristic of concrete (e.g. GWP, PE-NRE, E_{cm}, f_{cm}, f_{ctm}). For example, SP may significantly increase the strength of concrete, while the GWP and PE-NRe do not significantly change with its use (Figures 24-25, signs with *versus* without X marks). Contrary to SP, the incorporation of FA significantly decreases mechanical properties, GWP and PE-

NRe) of concrete mixtures. A similar conclusion was reached in other studies [83, 85, 100, 111]. Additionally, the incorporation of FRA also significantly decreases the mechanical properties of concrete, but it does not considerably affect the GWP and PE-NRe in spite of the fact that the transportation distance between the supplier and concrete plant is not very long. On the other hand, the incorporation of CRA may have the same effect on the GWP and PE-NRe of concrete, but it does not significantly affect its mechanical behavior.

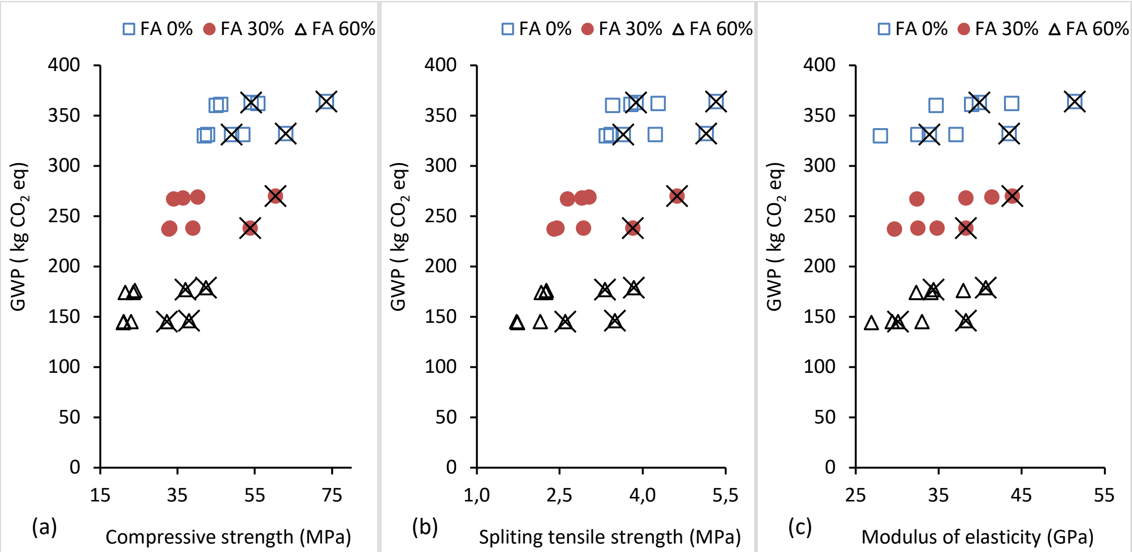


Figure 24 - Relationship between the GWP and (a) f_{cm}, (b) f_{ctm} and (c) E_{cm} of concrete mixtures containing various quantities of FA, and regardless of the type of aggregates (NA and RA)

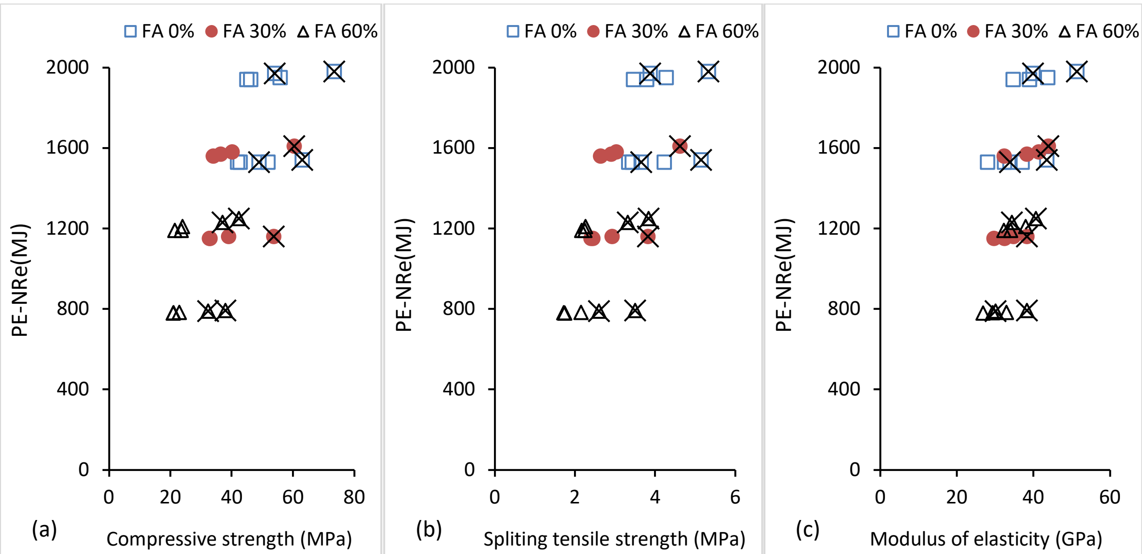


Figure 25 - Relationship between the PE-NRe and (a) f_{cm}, (b) f_{ctm} and (c) Ecm of concrete mixtures containing various quantities of FA and regardless of the type of aggregates (NA and RA)

In order to prove the above facts, an extensive literature review was made to understand the relationship between f_{cm} and GWP (Figures 26-28), and PE-NRe (Figures 29-31) of concrete mixtures containing various amounts of RA and FA. For that purpose, the actual [7, 101-105, 107, 112-122] and calculated

[39, 68, 94, 96, 111, 123-139] data were considered in the EI and resources use of 1m^3 of concrete. Apart from the mentioned studies, other works [21, 106-109, 140, 141] also studied the LCA of concrete, but were not considered due to the fact that they did not show the f_{cm} of the concrete mixtures. Additionally, the power type regression functions (GWP or PE-NRe = *Factor* · $f_{cm}^{0.46}$) are drawn for a 95% confidence interval at the lower and upper limits. The factors for the upper and lower limits are 85-100 and 40-50 for GWP (Figures 26-28), and 600-700 and 250-400 for PE-NRe (Figures 29-31), respectively.

Figures 26-31 show that even for the same concrete families (e.g. conventional, FA and RA concrete families), there is still a big scatter between the results. This can be explained by several factors. According to previous studies [7, 21, 39, 68, 94, 96, 101-109, 111-141], it can be concluded that, apart from non-conventional materials (e.g. FA, FRA, CRA and SP) that differently affect the GWP, PE-NRe and mechanical performance of concrete (explained before), other factors, such as w/b, aggregates geological nature, curing and mixing procedures, also affect the two mentioned characteristics in different ways. For example, the total EI and resources use of concrete, mortar or cement paste may not significantly change because of their water content while their mechanical performance does [142-146]. Similar facts can be seen for the effect of the physical and geological nature of conventional aggregates on the f_{cm} of concrete [147].

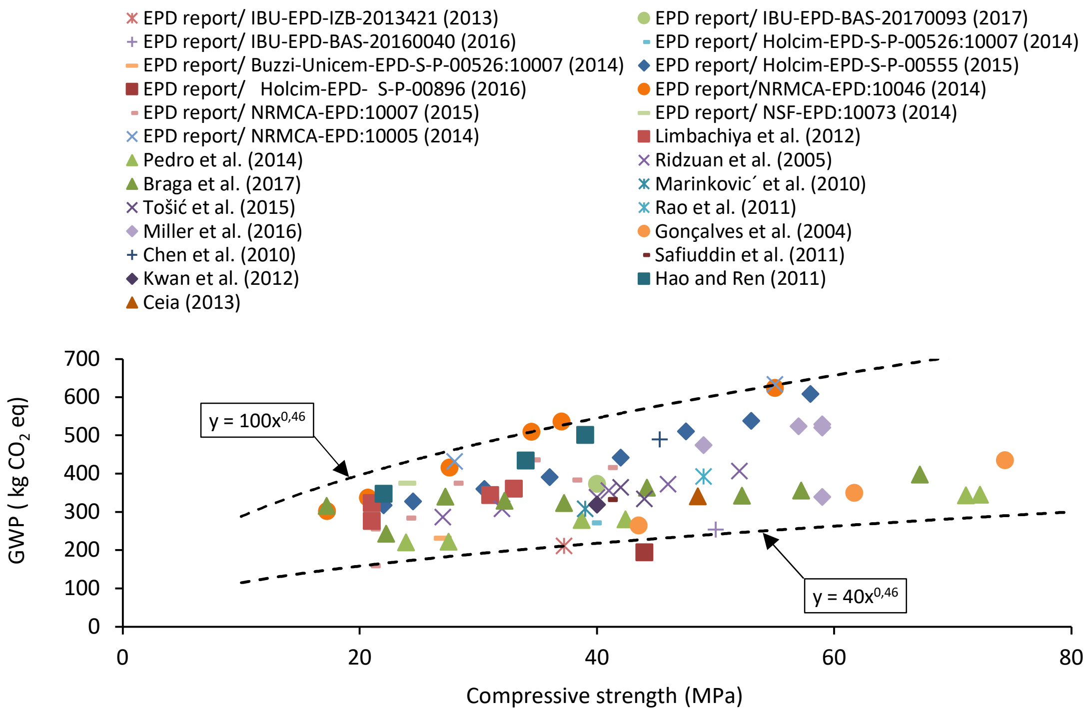


Figure 26 - Relationship between the GWP and f_{cm} of conventional concrete

Regarding the effect of non-conventional materials on the relationship of f_{cm} and GWP, and PE-NRE, the same trends found for conventional family mixtures can be seen, namely a big scatter between the concrete mixtures (Figures 27 and 30). For example, the total EI and resources use to produce RA may not be related to the quality of the source concrete [119, 148] while its quality considerably affects the mechanical and durability characteristics of concrete [3, 9, 23, 27, 149-154]. Additionally, the transportation scenario of RA may significantly affect the LCA of concrete [7, 12, 20, 25, 105, 155, 156] while it does not affect the mechanical performance of concrete. Similarly to RA concrete, the scatter for FA concrete is also big (Figures 28 and 31). This is also related to the transportation scenario and quality of the FA that differently affect the GWP, PE-NRe and mechanical performance of concrete [10, 11, 13, 81, 157-160].

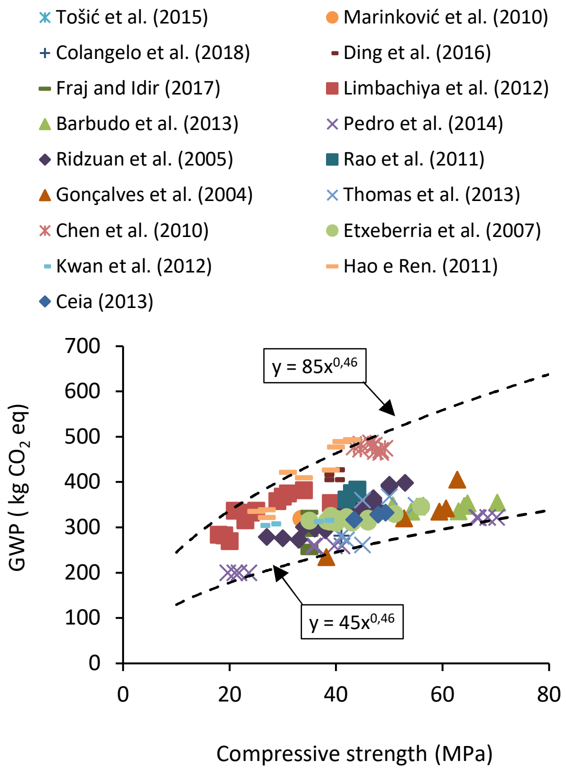


Figure 27 - Relationship between the GWP and f_{cm} of RA concrete

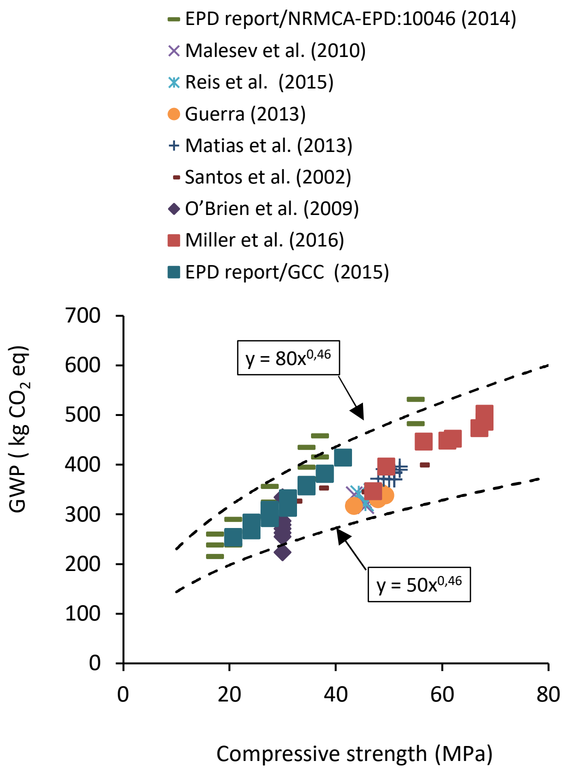


Figure 28 - Relationship between the GWP and f_{cm} of FA concrete

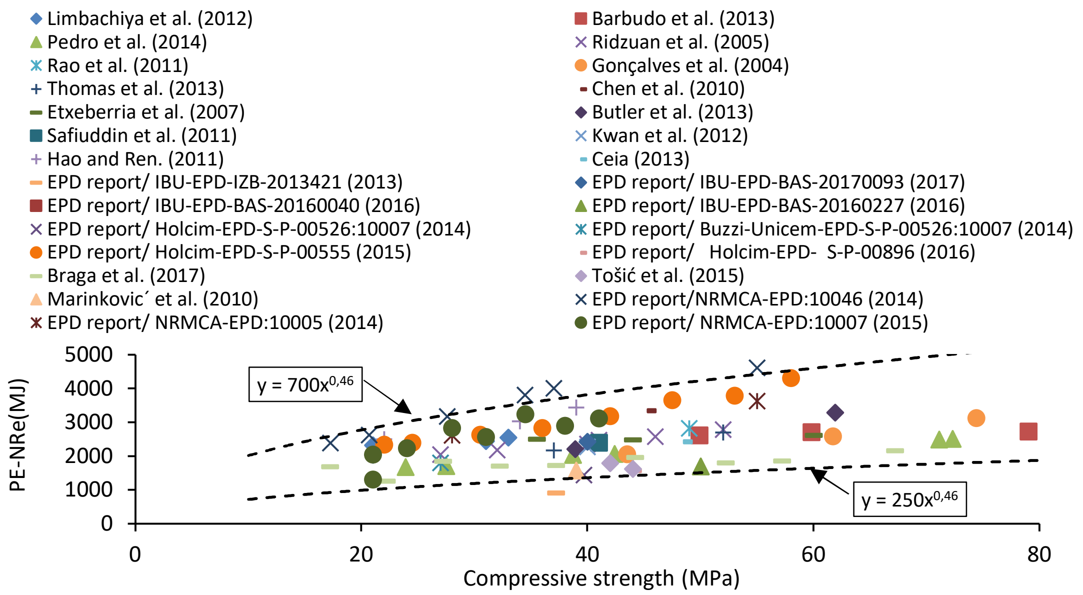


Figure 29 - Relationship between the Pe-NRe and f_{cm} of conventional concrete

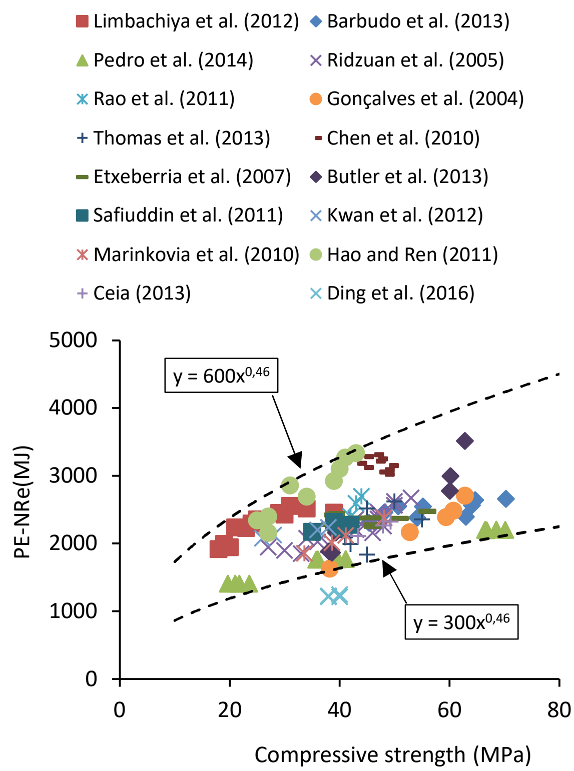


Figure 30 - Relationship between the Pe-NRe and f_{cm} of RA concrete

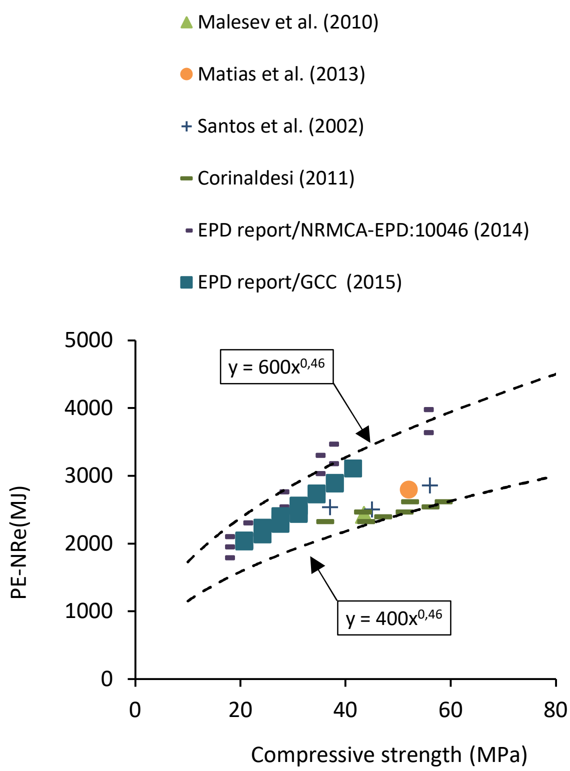


Figure 31 - Relationship between the Pe-NRe and f_{cm} of FA concrete

4 Conclusions

The conclusions of the present study made according to the results of this study and previous studies cited in Table 4 and Figures 3, 5, 7, 9, 13b, 14b, 16b, 17, 26, 27, 29 and 30, to understand the effect of the incorporation ratio of fly ash (FA) and recycled aggregates (RA) on the environmental impact (EI) and mechanical performance of concrete. The following outcomes can be drawn from the results.

Mechanical behaviors

- Similar tends can be found for the f_{ctm} and f_{cm} of the concrete mixtures containing FA and RA. As for f_{cm}, the results of this study and most of the previous works show that the incorporation of RA or FA in mixtures is harmful in terms of f_{ctm} when the cement content is not increased. In addition, E_{cm} decreased with increasing quantities of RA. Conversely to RA, the incorporation of FA did not significantly affect E_{cm}. By comparing the f_{cm} and f_{ctm} of the concrete mixtures with and without SP, the efficiency of SP in FA concrete is the highest (less sensitive), followed by conventional concrete and RA concrete. Regarding the sensitivity of E_{cm} of concrete mixtures to SP, the opposite conclusions can be seen. However, further research is required to comprehend the influence of SP on the concrete mixtures containing FA and RA.
- According to the results of previous researchers and the present study, the following global trends can be drawn for all mechanical properties (f_{cm}, f_{ctm} and E_{cm}) of the concrete mixtures containing FA and RA. For example, after one month, the mechanical development rate of the concrete mixtures containing FRA is higher than that of the mixtures with CRA. In terms of the joint effects of FA and RA, it can be seen that, after one month, the strength development rate of concrete mixtures made with both FA and RA is higher than that of the mixtures incorporating either FA or RA.

Environmental Impact (Energy consumption and global warming)

- According to the results of this study, the GWP and PE-NRE of mixtures seem not to be considerably affected by the incorporation of FRA and CRA, even though the transportation distance relative to NA was relatively short. Nevertheless, previous studies reported that the effect of RA on concrete mixtures depends on the transportation scenario.
- According to the results of this study and previous studies, although the transportation distance of FA was 2.7 times longer than that of OPC, the GWP and PE-NRe of the concrete mixtures significantly reduces with the quantities of FA. Contrary to FA, the GWP and PE-NRe of concrete mixtures does not affect with the use of SP.

Relationship between mechanical performance, and GWP and PE-NRe

- According to the relationship deducted based on the results of this study (same EI scenario) and previous studies (different EI scenarios), there are no clear relationships between “f_{cm}, f_{ctm} and E_{cm}”, and GWP or PE-NRe of the concrete mixtures containing non-conventional materials. This means that the incorporation of each non-traditional materials (e.g. FA, FRA, CRA and SP) differently affects each characteristic of concrete (e.g. GWP, PE-NRe, E_{cm}, f_{cm} and f_{ctm}). Thus, an optimization method (e.g. CONCRE***Top*** method - [18]) may be needed to find the optimum concrete in terms of mechanical performance, GWP and PE-NRe.

- In fact, the results show that even for the same concrete family (e.g. conventional, FA and RA concrete), there is still a big scatter between the results.

Finally, according to the results of this study and previous studies, it can be said that the optimum mixes in terms of concrete quality and EI are the ones made with incorporation of both FA and RA, rather than their individual incorporation, for most of the transportation scenarios.

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