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Concrete sustainability with very high amount of fly ash and slag

Sustentabilidade do concreto com altos teores de escória e cinzas volantes

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Abstract

This article approaches concrete mix designs where cement is replaced by high amounts of slag and fly ash, with the purpose of turning it into a more sustainable construction material, that is, an authentic green concrete. Mix proportions with fly ash, ground-blasted furnace slag, and Portland cement were studied in binary and ternary mixtures for compressive strength levels of 40 MPa and 55 MPa. The replacement of cement with mineral additions ranged from 50% to 90% in mass. Mean decreases of 55% in the energy consumption, 78% in the CO^2 *emissions, and 5% in the cost of the concrete* m^3*, plus an increase of 40% in the mean index of durability were obtained, all of which compared to the 40-MPa reference concrete. This study attests the technical, economical and environmental potentialities for the use of concrete mixtures with until 90% of fly ash.*

Keywords: *sustainability, slag, fly ash, durability, energy consumption,* CO_2 *emission, cost.*

Resumo

Este artigo versa sobre traços de concreto com substituição de cimento por altos teores de escória e cinza volante, com o objetivo de torná-lo um material de construção mais sustentável, ou seja, um autêntico concreto verde. Foram estudados traços de cinza volante, escória de alto forno e de cimento Portland em misturas binárias e ternárias para níveis de resistência à compressão de 40 MPa e 55 MPa. A subsituição de cimento por adições minerais, em massa, variou entre 50% e 90%. Foram obtidos, em média, decréscimos no consumo de energia de 55%, nas emissões de CO^2 de 78% e no custo do m^3 de concreto de 5%, e o índice médio de durabilidade aumentou 40%, todos comparados com o concreto de referência de 40 MPa. Este estudo atesta as potencialidades técnicas, econômicas e ambientais do uso de misturas de concreto com até 90% de cinza volante e escória.

Palavras-chave: *sustentabilidade, escória, cinza volante, durabilidade, consumo de energia, emissão de* CO_2*, custo.*

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1. Introduction

The civil construction consumes great part of the natural resources extracted from the planet and concrete is the greatest cause of this consumption, regarded as the second most consumed material by mankind, topped by water. Klee [1] reports that the cement production in 2002 was 1.56 Gt with an average growth of 4.4%/year and, Malhotra [2] says that, in the early 21st century, the production of concrete was 12.6 Gt. These figures show that the materials used in concrete represent twice as much the world's production for all of the remaining construction materials, which represents the consumption of 2.2 t per inhabitant/year.

Cement consumes 5.5 GJ of energy and liberates, approximately, 1 ton of CO_2 per ton of clinker corresponding to around 5% of the total emissions delivered in the atmosphere annually. Considering that each ton of cement requires 1.65 t of raw material or an annual extraction of 2.9 Gt for the cement industry, plus the mining of 12.5 Gt of aggregates for the concrete manufacture, totalizing 15.4 Gt, shows the magnitude of the material consumption by the concrete community. On the cement industry's part, these numbers highlight the intense use of natural resources and the gas emission which significantly contributes to global warming.

Mainly since the second half of the 20th century, part of the cement is being replaced by mineral additions, such as fly ash, slag, and other by-products, in order to decrease the environmental impact and increase concrete durability. The know-how and the mastering of both technology and utilization of these residues improved during that period, and they are widely used nowadays in several types of concrete structures. The advantages of this substitution are significant in the technical field, in the economic aspects and, mostly, in the environmental issues because of the reduction in CO_2eq emission, in energy consumption and, many times, in the direct cost, is proportional to the quantity of mineral additions used in the mixture instead of cement. The use of mineral additions - such as fly ash and ground granulated blast-furnace slag - in the concrete is worthy because it brings economic advantage when cement, a material of high added value in terms of cost and energy, is replaced by one or more types of mineral additions, by-products which feature economic and energetic low value. This action fits in the sustainability concept where everybody profits: the producer, for delivering a product at a lower cost (or almost always); the consumer, for acquiring a more durable material; and the society, for keeping the environment with lower levels of pollution and better preserving natural resources.

Fly ash and blast-furnace slag are the most used mineral additions due to their great availability and low cost as by-products. The worldwide production of fly ash in the early 21st century was between 480 Mt [2] and 660 Mt [3]. The pig iron production in 2007 was 920 MT [5], which projected an amount of 325 Mt for blast-furnace granulated slag.

The technical and economical advantages that mineral additions have, compared to cement in the concrete structures, are well known, especially durability. Some renowned researchers as P. K. Mehta, R. N. Swamy, V. M. Malhotra, and others published plenty of articles, where they emphatically exposed the advantages of using high amounts of industrial mineral additions instead of Portland cement in concrete production. Mehta [4] declares that superplasticized concrete mixtures containing 60 to 70% of fly ash or slag in the mass of the total cementitious material have shown high strength and durability at relatively early ages, and that large-scale cement replacement in concrete with these industrial by-products will be highly advantageous from the standpoint of cost economy, energy efficiency, durability and overall ecological profile of concrete.

Based on these guidelines, this work presents an experimental study aiming at quantifying the sustainability advantages of concrete containing from 50% to 90% of fly ash and blast-furnace slag, in binary and ternary mixtures. The cost of the materials, the CO_2eq emission, the energy consumption, and the parameters of concrete durability which influence in the rebar corrosion for 40-MPa and 55-MPa compressive strength levels were calculated. The results showed that the replacement of Portland cement with these mineral additions enabled, in one hand, a decrease in cost, as well as in CO_2eq emission, and in the energy consumed and, in the other

Table 1 – Chemical and physical characteristics of the cementitious materials

Chemical Analysis %	Portland Cement	Fly ash	Blast furnace slag
SiO_2	19.3	63.4	34.1
Al_2O_3	4.7	26.3	12.9
Fe_2O_3	3.0	3.9	0.6
CaO	63.4	1.9	41.1
MgO	1.8	1.0	8.2
SO_3	3.1	0.2	0.0
Na_2O	0.1	0.1	0.2
K_2O	0.9	1.2	0.6
Loss of ignition	3.0	1.1	0.0
Physical characteristics			
Specific gravity kg/dm^3	3.15	2.24	2.90
Blaine fineness m^2/kg	n.a.	n.a.	470
BET fineness m^2/kg	1800	350	n.a.

Table 2 – Mixture proportions per m³ of concrete (kg/m³)*

Mixture	w/cm	Portland cement	Fly ash	Slag	Admixture
REF	0.35	540			0.5
	0.45	393			
	0.55	309			
50FA	0.35	270	270		5.1
	0.45	197	197		2.4
	0.55	155	155		1.6
70S	0.35	162		378	2.7
	0.45	118		275	1.6
	0.55	93		216	1.2
90SFA	0.35	54	108	378	2.7
	0.45	39	78	275	0.8
	0.55	31	61	216	

* coarse aggregate for all mixtures: 1,018 kg/m³

hand, an increase in durability, highlighting a holistic advantage of replacing cement with high contents of mineral additions.

2. Experimental study

This experimental study concerns a research project developed in the Group for Studies and Research in Concrete (GEPECON) of the Post-Graduation Program in Civil Engineering of the Federal University of Santa Maria. The project goal was to study the durability of concrete with high contents of mineral additions, with and without addition of external lime, to observe the replacement of calcium hydroxide reserve depletion, due to the cement decrease in the mixtures and, also, for its consumption by the pozzolanic reactions. In this work are presented only the mixtures without hydrated lime.

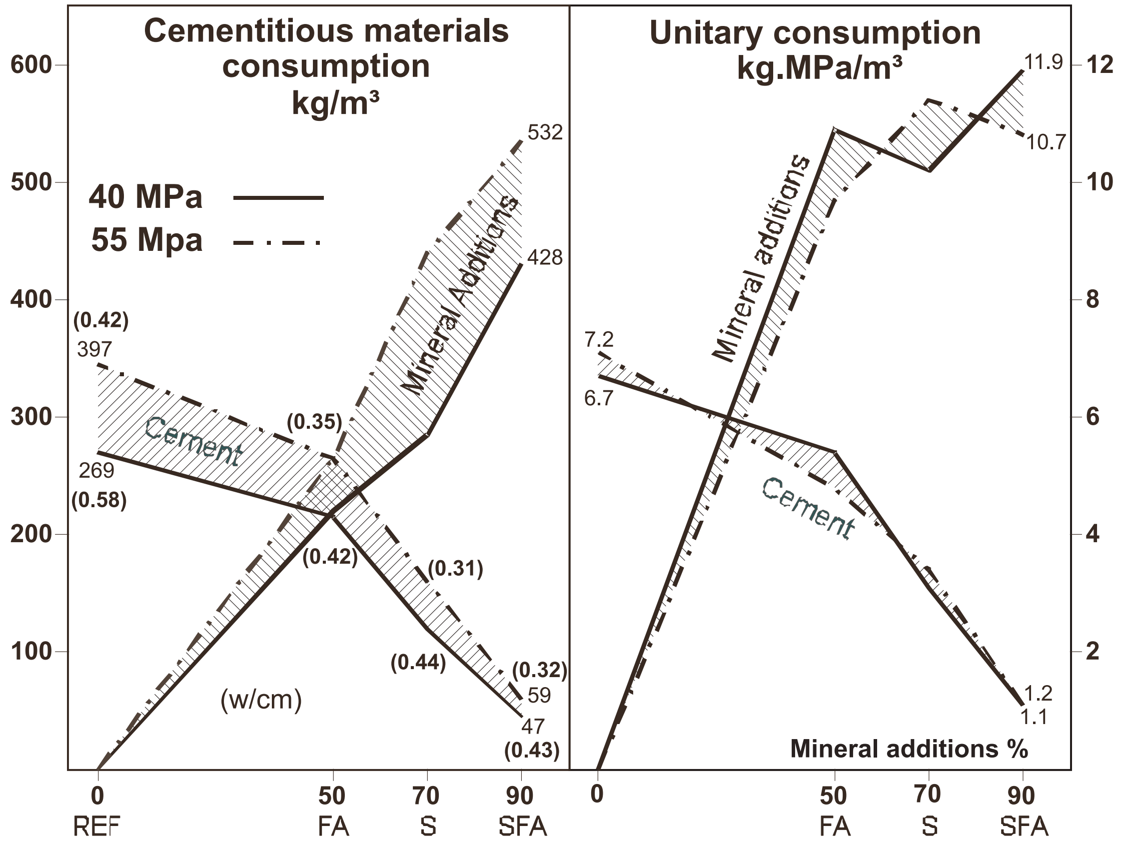
The following materials were used in the concrete mixtures: type V high-early strength Portland cement, according to Brazilian Standard NBR 5733 (similar to ASTM type III); local natural quartzous sand with maximum characteristic diameter (MCD) of 4.75 mm and fineness modulus (FM) of 2.2; coarse diabasic aggregate with MCD = 19 mm and FM = 6.6; and policarboxilate ether (PCE) based superplasticizer admixture. The chemical analysis and physical characteristics of the cementitious materials are presented in Table 1.

The design proportions were calculated with a cement replacement, in mass, with 50% of fly ash (FA), 70% of blast-furnace slag (S), in binary mixtures, and 20% of fly ash and 70% of slag (SFA), in ternary mixtures. Due to the different specific gravity between cement and mineral addi-

Table 3 – Results of the compressive strength and the durability tests (91 days)

Mixture	w/cm	91 days MPa	Carbonation Coefficient mm.week$^{-0.5}$	Chloride Penetration coulomb	Retained Chloride mmol/kg	Cl^-/OH^- ratio
REF	0.35	72.4	0.10	2380	31.7	0.76
	0.45	51.8	1.31	2800	31.6	1.00
	0.55	46.1	3.53	3134	33.0	1.51
50FA	0.35	59.1	3.95	754	21.9	0.69
	0.45	30.5	7.49	925	27.4	1.44
	0.55	25.4	14.61	1190	28.9	2.10
70S	0.35	49.1	1.02	840	34.5	0.37
	0.45	39.1	7.10	1030	36.5	0.71
	0.55	32.6	9.08	1140	44.3	0.90
90SFA	0.35	46.1	4.64	448	23.6	2.36
	0.45	33.1	6.70	552	29.4	1.20
	0.55	20.0	14.13	651	31.0	1.32

Figure 1 – Total and unitary cementitious material consumption for 1 m^3 of concrete



tions, the amount of sand was corrected in order to maintain the same mortar volume of 53% in concrete. The mixtures were proportioned with 0.35, 0.45 and 0.55 water/cementitious materials (w/cm) ratio at the same slump range of 60±15 mm. The quantity of materials per m^3 is presented in Table 2. It is relevant to point out that, for the Portland cement consumption, the 90 SFA mixtures contained from 31 kg/m^3 to 54 kg/m^3, only, that is, 10% of the reference concretes.

For the compressive strength tests, 10 x 20 cm specimens were molded according to Brazilian Standard NBR 5738 and tested according to NBR 5739. For the durability study, tests pertinent to rebar corrosion were selected aiming at observing the influence of the high contents of mineral additions in the concrete specimens submitted to those variables that are important to establish the useful life of actual structures. The following durability tests were performed: chloride-ion penetration (ASTM C 1202), total acid-soluble chloride (ASTM C 114 and C1152), pH potential for calculation of the Cl^-/OH^-, and accelerated carbonation test in climatic chamber with 5% of CO_2, temperature of 23ºC, and 72% of relative humidity, with carbonation depth measurements at 4, 8 and 12 weeks. The other durability tests were performed at 91 days.

3. Test results

Table 3 presents the test results for the axial compressive strength as well as for durability, all of them at 91 days. This age was selected in order to highlight the hydration and pozzolanic reactions of fly ash and slag that are slower than the Portland cement only. It must be taken into account that the most important concrete structural members are charged with the total design load in ages higher than 3 months.

Since the specimens' compressive strength ranged between 25.4 and 72.4-MPa at 91 days, two concrete grades for the sustainability study were selected: 40-MPa to represent conventional concrete with f_{ck} ≈ 35-MPa, and 55-MPa for high-performance concrete with f_{ck} ≈ 50-MPa. Some data for CAD study were calculated with slight extrapolation (< 10%), in relation to the test results of the mixtures 70S and 90SFA. For the durability study, the variables were statistically correlated, by non-linear regression, with the respective compression strength data. All statistical regressions presented coefficient of determination $r^2 \geq 0.85$.

4. Sustainability study

4.1 Data for sustainability study

4.1.1 Cementitious materials

The amount of cementitious materials per m^3 is displayed in Figure 1. While the cement consumption decreased, the amount of min-

Table 4 – Unitary coefficients of cost, energy and CO_2 emissions per ton

Materials	Transport km	Cost [a] US$.$t^{-1}$	Energy consumption MJ.t^{-1}	Co_2 emission kg.t^{-1}
Cement	200	120.00	5780 [b]	1090 [c] + 584 [d]
Fine aggregate	60	13.00	90	3
Coarse aggregate	60	20.00	140	4
Fly ash	200	20.00	300	10
Slag	200	60.00	310	10
Admixture	200	4,050.00	15.030	94
Water	-	0.75	1.130	5

[a] Regional average costs, CIF, valid for January 2009, at the exchange rate of R$ 2.40/US$

[b] Average energy consumption by wet and dry processes (9)

[c] Average Co_2 emissions of limestone, fuel and electricity (10)

[d] See calculus in the text below

eral additions increased at a higher degree, caused by the drop of the w/cm ratio needed to reach the desired strength level. So, the higher the contents of mineral additions, the lower the w/cm because, according to Isaia et al. [6], to reach a desired strength level, the paste must contain a minimum amount of C-S-H (chemical effect) and/or closer contact between the grains (physical effect), in order to reach the target strength. As the efficiency of the mineral additions is lower than the Portland cement, a higher amount of cementitious material is needed to counterbalance the cement substitution, in mass. This behavior is shown by the unitary strength analysis because, while the unitary cement consumption decreases, in average, from 7 to 1 kg.MPa/m³ (6 times drop) when the contents of mineral additions increases, the cementitious material rises until 11 kg.MPa/m³, in order to provide a denser pack for the paste matrix and transition zone.

For the reference mixture, Figure 1 shows a cement consumption of 269 kg/m³ and 397 kg/m³ for 40 and 55-MPa strength levels, respectively, while for the mixtures with 20% of fly ash and 70% of

Figure 2 – Unitary costs (US$/m³) for 40 and 55-MPa strength grades

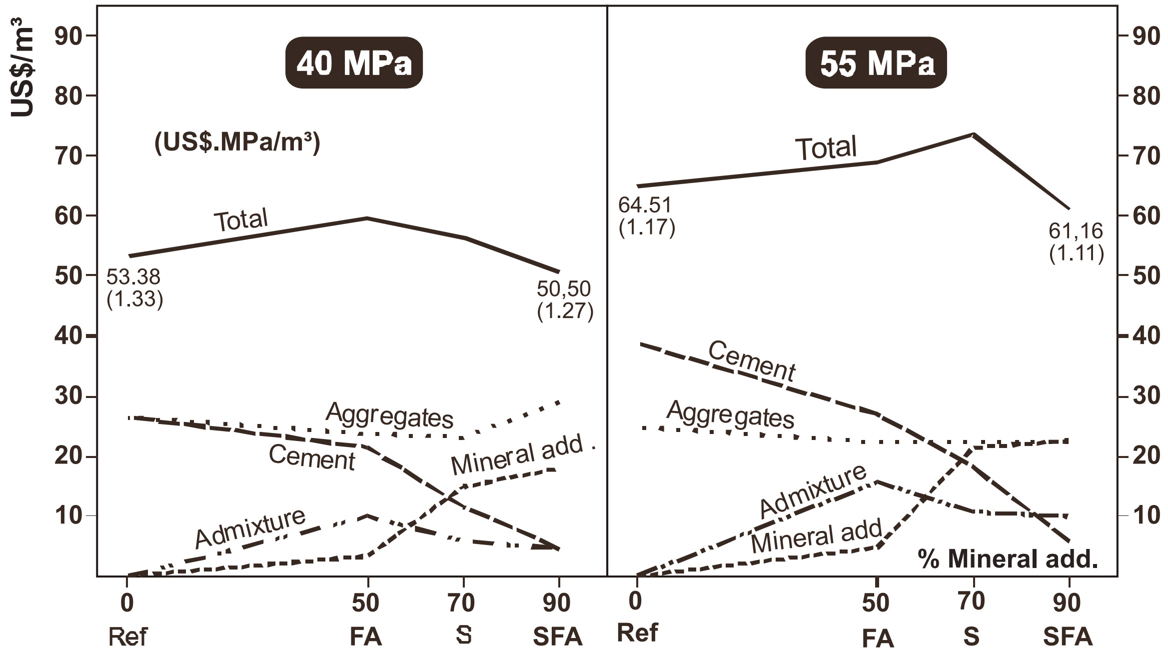
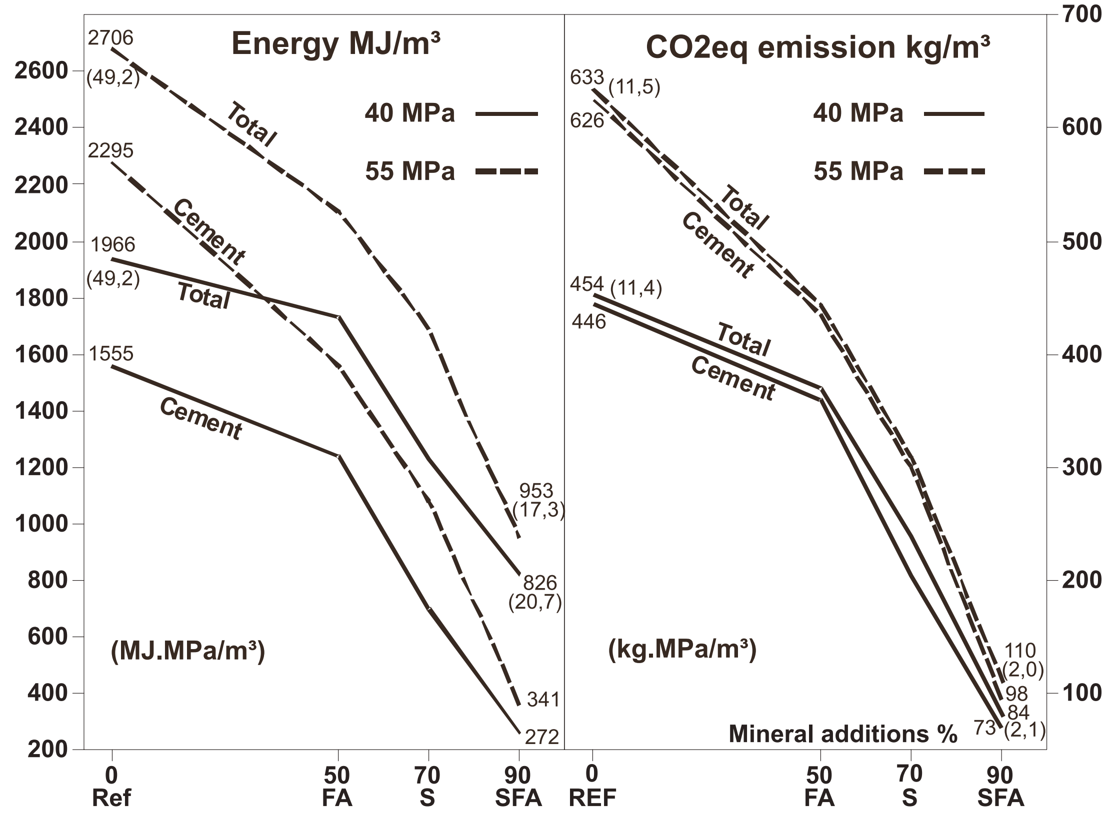


Figure 3 – Total and unitary embedded energy and CO_{2eq} emissions per m³ for 40 and 55-MPa concrete grades



slag (90SFA), these figures decreased to 47 kg/m³ and 59 kg/m³, representing an average fall of 84%.

4.1.2 Unitary cost, energy consumption and CO_{2eq} emission

Table 4 presents the unitary coefficients of cost, energy and CO_2 emissions, per ton. All figures include freight at the appointed transport distance, round trip, to the average cost of US\$ 0,02/t.km^{-1} [7], with energy consumption of 1.4 MJ/t.km^{-1} [8] and CO_2 emission of 0.045 kg/t.km^{-1} [9]. The distances were arbitrated for a medium-sized city, simulating a construction located at the outskirts of an urban center.

For the cement manufacture, the CO_2eq average emission for limestone, fuel and electricity was added by part of NO_x = 1,85 kg.t^{-1} [11], multiplied by a global warm-equivalence potential (GWP) equal to 310 [12] to attainment the CO_2eq's 1.85.310 = 584 kg.t^{-1}. For the sand and coarse aggregate only the extraction energy consumptions were considered, to be the arbitrated 0.1 MJ/t^{-1} for both aggregates. The energy consumed by the transport and deposition of fly ash and slag was assumed as [8] and the respective CO_2eq emissions were arbitrated in 1.0 kg.t^{-1}. It was considered, for the admixture, 30% of the consumed energy and of the CO_2eq emission for the production of 1 ton of naphtha manufacture, because these admixtures, on average, present 30% of solids. The energy of water was calculated considering the consumption of a 5-HP pump with 12m³/h flux, and the CO_2eq emission was estimated for water capture, transportation, treatment and storage.

4.1.3 Concrete cost

Figure 2 shows that cement presented higher cost for the REF and 50FA mixtures compared to others materials. When the contents of mineral additions increased from 70 to 90%, the aggregates were the materials with preponderant cost, higher than the mineral additions for the 90SFA mixture. The total cost of REF_{40} was US\$ 53.38 and for the 90SFA US\$ 50.50, a 5.4% drop, almost the same for the REF_{50}, 5.2%. Obviously, all mixtures for 50-MPa grade showed higher total cost than those for 40-MPa. However, for the unitary cost, per MPa (in brackets), the former were 12% and 12.5% lower, respectively, for REF_{55} and $90SFA_{55}$ mixtures. The unitary figures show better cost efficiency for the mixtures with higher strength.

4.1.4 Energy and CO_{2eq} emission

Figure 3 shows that, for the REF mixture, the cement accumulated from 79% to 85% of the total energy, respectively for the 40 and 55-MPa strength levels. As the amount of mineral additions increased, the energy of the cement decreased, reaching, for 90SFA mixtures,

Table 5 – Durability test results for 40 and 55-MPa

f_c MPa	Mixture	Carbonation Coefficient*		Cl^- penetration		Retained Chloride		Cl^-/OH^- ratio		Mean index	
		mm. $w^{-0,5}$	Ind. I	Coul. C	Ind. I	mmol/ kg	Ind. I	Cl^-/OH^-	Ind. I	Total	Per MPa
40	REF	6.0	100	3360	100	32.9	100	1.6	100	100	100
	50FA	6.4	107	886	26	24.9	76	1.1	69	70	70
	70S	5.9	98	990	29	38.0	116	0.6	38	70	70
	90SFA	5.4	90	487	14	25.8	78	1.3	81	66	66
55	REF	1.3	22	2775	83	32.1	98	1.1	69	68	50
	50FA	3.9	65	749	22	22.4	68	0.7	44	50	36
	70S	0.4	7	779	23	31.4	95	0.3	19	36	26
	90SFA	4.2	70	421	13	23.3	71	1.0	63	54	39

Carbonation coefficient: mm.week-0.5
Durability performance index: I40MPa = 100

approximately 1/3 of the total embedded energy. For mineral additions mixtures, the total energy decreased until 58% for 40-MPa level and 52% for 50-MPa. The unitary energy consumption (in brackets) decreased from 49.2 $MJ.MPa^{-1}$ for the REF_{40} to 20.7 and 17.3 $MJ.MPa^{-1}$, for the $90SFA_{40}$ $90SFA_{55}$, representing a reduction of 58% and 65%, respectively. These figures demonstrate the ad-

Figure 4 – Performance indexes for cost, energy, CO_{2eq} emission and durability pertinent to the 40-MPa compression strength level

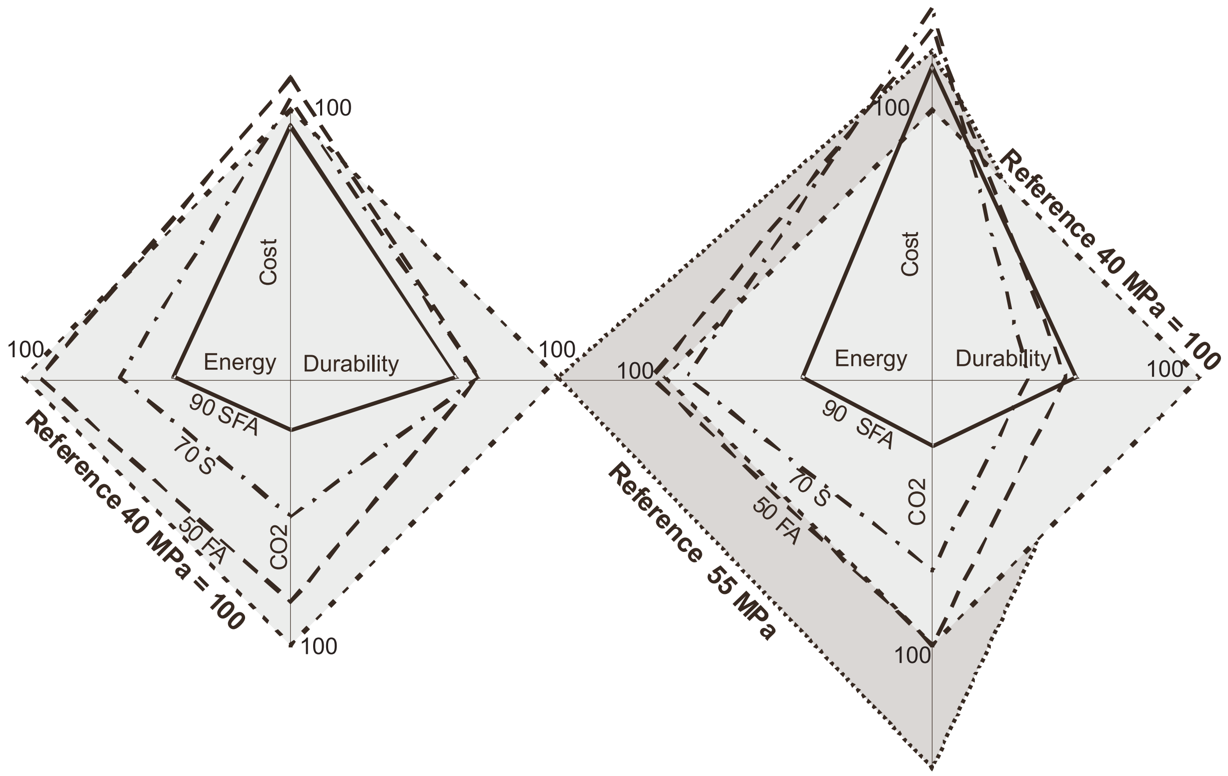
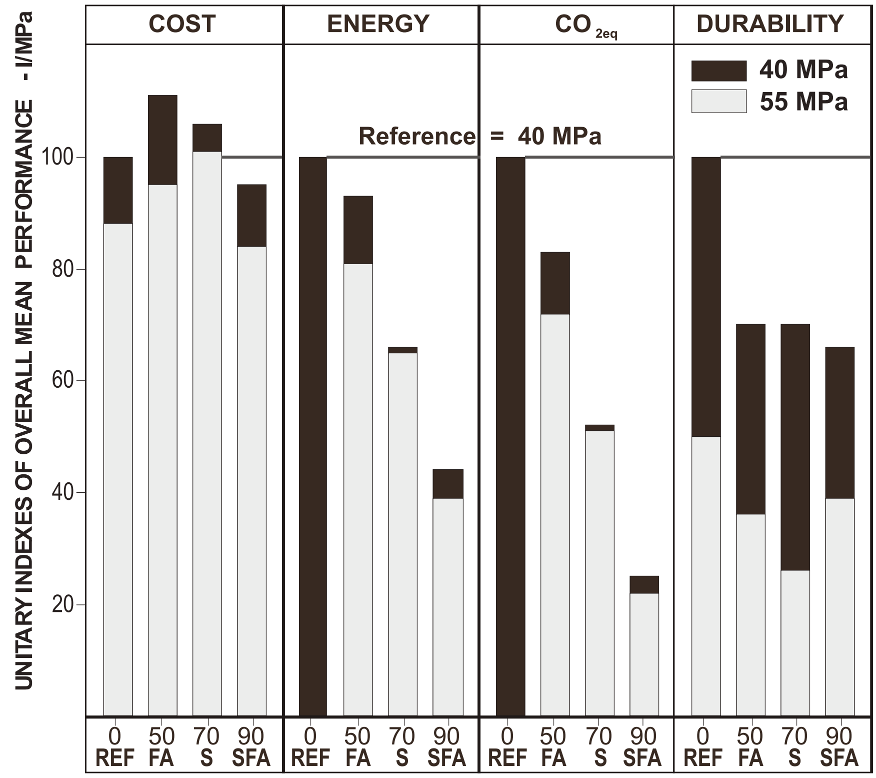


Figure 5 – Unitary indexes for the overall mean performance (I_m/MPa)



vantage of the smaller specific energetic consumption when the concrete compressive strength is increased.

For the CO_{2eq} emissions, Figure 3 shows a significant environmental gain when cement is replaced with mineral additions, because more than 95% (except for the 90SFA with 87%) of the concrete CO_{2eq} emissions come from Portland cement. For the 90SFA mixtures, the reductions reached 81% and 76%, respectively, for the 40 and 55-MPA levels, respectively, pertinent to the REF_{40}. The unitary emission revealed that the REF_{40} presented 11.4 kg/MPa, while all the others with mineral additions had smaller emanation, reaching 1.8 kg/MPA (-84%) for the $90SFA_{55}$ mixture. So, the latter emit from 5 to 6 times less CO_{2eq} than the respective reference concrete, per MPa, highlighting again the advantage of using concrete with higher compressive strength.

4.1.5 Durability

The results of the durability tests pertinent to the rebar corrosion, for 40-MPa and 55-MPa compressive strength, showed at Table 5, demonstrate the best performance of all variables, making it evident that there is technical viability for cement replacement with mineral additions, up to 90% in content. These data reveal that $90SFA_{55}$ mixture presented a carbonation coefficient of 4.2 mm.week$^{-0.5}$ (42-mm carbonation depth in 100 years), chloride penetration of 421 coulomb (very low, according to ASTM C1202), 23.3 mmol/kg of total retained chloride, and 1.0 Cl^-/OH^- ratio, that is, a very durable concrete against corrosion attack.

4.2 Analysis of the results

In order to compare all test results together, the 40-MPa strength level data were taken as performance index I = 100; the others were calculated proportionally, even for the 55-MPa grade. For the durability variables the mean indexes of Table 5 are plotted in Figure 4. In general, except for the cost, all indexes related to the energy, CO_{2eq} emission and durability decrease as the contents of mineral additions in the mixtures increased.

Regarding the REF_{40}, the cost of the 90SFA mixture was 5% lower; for REF_{55}, only the durability performance was benefited by comparison with the same base, because the other indexes are significantly dependent on the contents of cement in the mixture, a material of higher cost, which consumes more energy and emits more CO_{2eq}.

Figure 5 presents the unitary indexes for the overall mean performance assuming REF_{40} = 100. Except for the cost indexes for the 50FA and 70S mixtures, for 40-MPa grade, all others variables presented lower figures compared with the reference, as lower as higher the contents of mineral additions. The 90SFA mixture showed the lowest indexes for the CO_{2eq} emission, with a mean decrease of 81% (I = 19), and for energy, with a mean decrease of 61% (I = 39). The unitary analysis per MPa reveals the advantage of the use of higher strength level, because these mixtures, besides presenting higher cementitious materials consumption and cost, are more efficient and present better cost/benefit ratio compared to the real test data.

Figure 6 – Overall (OI) and unitary (UI) mean performance indexes for cost, energy, CO_{2eq} emission and durability

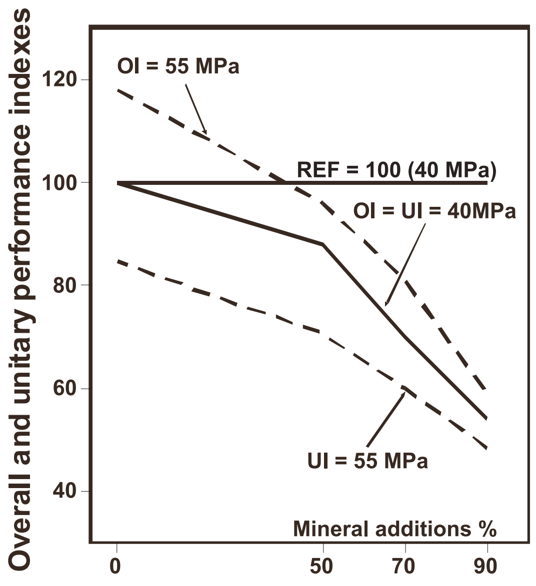


Figure 6 shows the overall performance index (OI), regarding REF_{40} = 100. The REF mixture increased to 117 for 55-MPa grade, while, for the unitary index (UI), it decreased to 85. These indexes show that the increase in strength promoted higher efficiency for the mineral additions mixtures, not only for the durability but, also, for the environmental variables, besides cost. For the unitary indexes, the mixture 90SFA revealed a decrease of 44% for 40-MPa and 56% for 55-MPa.

Table 6 presents the differences between the data of a given mixture and the respective reference concrete. It was introduced the variable cement as a comparison term, because it is the most important one, which influences the others from the environmental point of view. The cement consumption decrease was proportional to the contents of mineral additions, reaching 84%, on average, for the mixture 90SFA. For the 50FA and 70S mixtures, the cost presented an increase from 6 to 15% while, for the 90SFA, a decrease of 5%.

After the cement, the variables that decreased the most, for the 90 SFA mixture, were energy consumption, from 58% to 65%, and CO_2 emission between 81% and 83%. This last one presented figures close to those of the cement because, practically, all CO_2 emitted by the concrete is due to this binder.

Under a durability focus, the differences between the mixtures with mineral additions and the reference mixtures ranged from 30 to 34% for 40-MPa and 26 to 38% for the 55-MPa. These data are quite different from the cement figures in terms of percentage, because the mechanisms that govern the corrosion process depend on other parameters of the cementitious material (pore and grain size refinement or ionic pores solution), rather than cement (clinker) only.

These figures demonstrate that sustainability of the concrete structures relates directly to the replacement of cement with mineral additions and to the compressive strength level. The less cement is contained in concrete, the higher the characteristics of strength, and the lower the energy consumption and CO_2 emission.

5. Conclusions

Concrete, the most consumed construction material worldwide, is the ideal repository to shelter industrial residues as blast-furnace slag and fly ash, cementitious materials that possess technical, economical, and social advantages. In this experimental study, the results highlighted that the use of until 90% of mineral additions to replace the cement mass, the durability average indexes, for the four studied variables connected with the rebar corrosion, decreased 34% to 40-MPa compressive strength and 46% to 55-MPa, taking I_{40MPa} = 100. The cost decreased 5% for the 90SFA mixture for 40-MPa and equal value regarding REF_{55}.

The energy consumption decreased heavily with the content increase of mineral additions because the cement, alone, contains more than 80% of the total embedded concrete's energy. For the mixture with 90% of mineral additions, there was an energy decrease of 58% for 40-Mpa, and of 52% for 55-MPa. The reductions of CO_2 emission were, respectively, 81% and 76% the highest reduction among all the observed variables.

Table 6 – Differences between mineral additions mixtures and the reference concrete (% is associated to the REF_{40})

f_c MPa	Mixture	P. cement		Cost		Energy		CO_2		Durability	
		Δ kg/m³	%	Δ US$/m³	%	Δ MJ/m³	%	Δ kg/m³	%	Δ Index	%
40	50FA	52	19	-6.87	-11	202	10	84	19	30	30
	70S	147	55	-4.04	-6	741	38	240	53	30	30
	90ECV	222	83	3.48	5	1140	58	370	81	34	34
55	50FA	130	33	-6.10	-8	614	23	188	30	18	26
	70S	209	53	-11.67	-15	1027	38	322	51	21	47
	90ECV	338	85	4.04	5	1753	65	523	83	14	21

The unitary analysis per MPa for the energy, CO_{2eq} emission and durability prove that the decreases were higher for 55-MPa than for 40-MPa, revealing that the advantages increased when the compressive strength was upgraded. Thus, it had been proved that high-strength concretes, besides presenting higher durability by strength unit, also showed best cost/benefit relationships, despite the higher total actual costs.

The results of the present article show that the use of high contents of mineral additions compare technical and economic viability, because there is availability of these residues, throughout the world. Besides, they confer higher durability, significant environmental earnings as well as lower financial costs. The use of large amounts of mineral additions would be an initiative where everybody would gain and, in such manner, they would be contributing, with concrete measures, for the building of environmental sustainability.

The results of the case study show a feasible way to use such huge available amount of slag and fly ash existing all over the world.

6. Acknowledgements

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