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Mechanical and transport properties of 10 years old concretes prepared with different coarse aggregates

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HIGHLIGHTS

- Ten years old concretes incorporating different coarse aggregate were studied.
- Three damaged levels were induced by air drying, high temperature and loading.
- Mechanical and transport properties were measured.
- Mesostructural characteristics as crack density and interface length were measured.
- The relationship between internal damage and concrete properties is discussed.

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ABSTRACT

Many studies have discussed the effects of coarse aggregate on the mechanical properties of concrete, but this is not the case of the transport properties. The evaluation of the behavior of old concretes becomes of interest as the presence of microcracks can modify its response. Concretes prepared with different coarse aggregates (granitic and quartzitic crushed stone and river gravel, maximum sizes 19 and 38 mm) damaged by drying shrinkage after the exposure during 10 years to moderate environmental conditions are studied. To analyze greater levels of damage the residual properties of the same concretes after high temperature exposure or load-induced cracking are also studied. The paper includes the evaluation of mechanical and transport properties together with a characterization of the internal structure of concrete (density of cracks, density and perimeter of coarse aggregates). The compressive strength decreased after 10 years exposed to laboratory ambient; the concrete prepared with river gravel 38 mm maximum size showed the largest reductions while concretes prepared with quartzitic stone maintained the initial strength level. The different damage processes affect the transport properties in different manner according to the distribution and density of induced cracks; water permeability seems to be the mechanism most sensitive to the type and size of coarse aggregate.

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1. Introduction

The searches of tools that contribute to the sustainable development, and the permanent increases in reparation costs, have turned the durability of concrete structures one of the major challenges for the construction industry.

The degradation of concrete structures can be promoted by several process like reinforcement bars corrosion, sulfate attack, and alkali silica reaction, among others. In this sense the movement of fluids within concrete, where different transport mechanisms can be involved (absorption, diffusion, permeation), affects the durability and therefore the integrity of the structures [1].

The transport of fluids in concrete is controlled by the volume of paste, the porous structure of the matrix and interfaces, and the presence of cracks. It is well known that the permeability is strongly affected by the w/c ratio, as it controls the capillary porosity of the system. It is also known that comparing mixtures prepared with the same water/cement ratio, the permeability increases as the aggregate size increases. This increase in permeability can be attributed to a greater porosity at the interfaces when compared with the bulk matrix and in many cases to the presence of microcracks in these transition zones; being the interface cracking more severe as the aggregate size increases [2]. It is also recognized that the presence of cracks increases the permeability of the material favouring the ingress of aggressive agents

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that contribute to the structure degradation; Reinhardt and Joos [3] showed a strong relationship between the permeation rate and the crack width.

Cracking in concrete structures is a time dependent process, which in many practical applications is enhanced by drying shrinkage, and, among other factors cyclic loads, deleterious reactions, and temperature variations. There is a general agreement on the importance of matrix – aggregate bond as the interfaces are the weakest link of the composite material; being the critical interfaces those between coarse aggregates and mortar. The type and size of coarse aggregate can enhance crack formation; according to the aggregate used, the water content at the interfaces can be modified (bleeding, absorption) and, at the same time differences in stiffness and thermal expansion coefficients of the aggregate particles can modify the grade of cracking at the interfaces.

Many studies have shown the effects of aggregate interfaces on the mechanical and fracture properties of concrete. The failure mechanisms under loading are affected by the characteristics of the coarse aggregates, specially their surface texture and shape, and on the strength differences between aggregates and matrix in the case of high strength concretes [4,5]. Usually crack propagation starts at the interfaces and later cracks grow through the matrix; coarse aggregates arrest crack growth producing meandering and branching of cracks, nevertheless some particles can be fractured according to the characteristics of the phases. The preponderance of interface on matrix cracks explains the great influence of the amount and size of aggregates on the inelastic behavior of the material [6].

It is recognized that strength and transport properties are not always strictly related, as the changes in concrete internal structure affect in a different way mechanical and transport properties. Contrary to what happened with the mechanical behavior, it is not frequent the analysis of the effects of interfaces, aggregate type and size and microcracking on the transport properties.

Analyzing the effects of size, content and shape of the aggregates in concrete properties Basheer et al. [7] found that the size and tortuosity of the transition zone can vary significantly with some of the aggregate characteristics. An increase in coarse aggregate size in concrete promotes an increase in air permeability, sorptivity, water permeability and ionic diffusivity. From microstructural analysis at the interfaces it was confirmed that the coarser the aggregate the more porous the transition zone is, concluding that in order to design durable concretes, it is preferable to use smaller size aggregates and a low average aggregate size for the combined fine and coarse aggregates.

The influence of microcracking on the mass transport properties of concrete was studied by Samaha and Hover [8], showing that internal damage associated to shrinkage (produced by thermal damage) appears to have greater influence on transport properties than short term load-induced cracking. Regarding the types of cracks, Samaha and Hover [8] observed that mortar cracking was far more influential in increasing the rate of mass transport in concrete than cracking at the aggregate-paste interface. The mass transport properties of concrete were not substantially affected by loading below the 75% of the maximum load capacity. Hearn [9] also differentiates drying and load-induced micro-cracks and indicates that shrinkage cracks produce high increments in permeability while loads up to 80% of maximum load do not affect permeability. Regarding aggregate effects, there were found decreases in permeability as the content of aggregates increases, probably due to their effects in reducing shrinkage. Finally, it was found an increase in the weight of absorbed water due to microcracking produced by external loading [8].

The effects of microcracks can also vary when different transport mechanisms are considered. Mortar permeability was more sensitive to the presence of microcracking and to changes in total porosity than diffusivity or sorptivity. When concretes and mortars are compared, both of them have about the same diffusivity and sorptivity, but concrete presents significantly higher permeability, attributable to more microcracking [10].

In a previous work the authors studied the behavior of a 19 mm maximum size granitic crushed stone concrete that was exposed to air drying or to high temperature (150 and 500 °C). When compared with moist cured specimens, air dried, 150 °C and 500 °C samples showed reductions in compressive strength of 6%, 14% and 20%; for the same conditions the reductions in the modulus of elasticity were equal to 10%, 17% and 50% respectively [11]. The study, that also included the analysis of concretes damaged by alkali silica reaction, concluded that the width, the density and the type of cracks have a strong incidence on transport properties, but the effect of each parameter depends on the main transport mechanism involved in each test. In this study it was found that the velocity and capacity of capillary absorption grew as the crack density increases until a maximum is reached and then decreased, even though the density and crack width continued increasing. On the other hand the permeability tests showed a direct relationship with the level of damage, the coefficient of permeability grew constantly as the density and width of cracks increased.

Summarizing, a general review indicates that although concrete durability is mainly related to the matrix properties, the bond characteristics, shape and size of the aggregates can affect the transport properties as they can lead to different crack patterns. It is well known that concrete properties change with time, nevertheless most studies on the effect of aggregates were performed on relative young concretes. In old concretes microcracks produced by drying shrinkage are usually present and this can modify the response of concrete, then the evaluation of the behavior of old specimens becomes of interest.

Improvements in the knowledge of the relationship between mesostructural aspects and transport properties of concrete are necessary in order to produce more durable concrete in the future. As a contribution, this paper evaluates the internal structure, the transport properties, as well as the mechanical characteristics, of concretes exposed during 10 years to moderate environmental conditions (mainly damaged by drying shrinkage). In addition, the residual properties of the same concretes after greater damage processes (high temperature exposure or load-induced cracking) are considered. The analysis involves the relationships between the cracks density and matrix-aggregates interfaces length with concrete permeability, capillary absorption, strength and stiffness.

2. Experiences

The experimental work was performed on concrete specimens that remained indoors at the laboratory during 10 years. Six 40 MPa compressive strength concretes with the same mortar characteristics (water/cement ratio and cement type) incorporating different types and sizes of coarse aggregate, were studied.

2.1. Coarse aggregates characteristics

Three different types of coarse aggregates were used: granitic crushed stone (G), quartzitic crushed stone (Q) and a river gravel (R) composed by particles of different types of rocks. The selected aggregates present significant differences in mechanical properties, shape, texture and bond strength. The granitic crushed stone has irregular shape, rough texture and low absorption. The quartzitic crushed stone has irregular shape and rough texture, and it has the highest water absorption and the lowest strength. The river gravel is composed by round particles of many different types of

Table 1
Characteristics of the coarse aggregates.

Aggregate type	Quartzite		Granite		River gravel	
Particle size distribution (pass %)						
Sieve/coarse aggregate fraction	Q 19	Q 38	G 19	G 38	R 19	R 38
37.5 mm	100	100	100	100	100	99
26.5 mm	100	92	100	87	100	74
19.0 mm	93	61	92	48	92	56
13.2 mm	51	15	44	19	49	30
9.5 mm	27	8	26	11	31	19
4.75 mm	0	0	0	0	0	0
Fineness modulus	6.81	7.31	6.82	7.41	6.78	7.27
Shape	Irregular		Irregular		Round	
Texture	Rough		Rough		Smooth	
Water absorption (%)	2.13		0.80		1.10	
Los Angeles abrasion (%)	61		22		16	
Density	2.48		2.65		2.65	
Estimated strength, punctual loading						
Compression (MPa)	130		190		190	
Tensile (MPa)	10		14		12	
Rock strength						
Compression (MPa)	86		114			
Flexure (MPa)	14.8		15.5			
Interfaces bond strength (MPa)						
Mortar flexural strength 7.7 MPa	6.4		5.9			
Mortar flexural strength 8.5 MPa	8.0		7.0			
Mortar flexural strength 10.8 MPa	9.9		8.9			
Capillary absorption						
Capacity (g/m^2)	940		100		200*	
Sorptivity ($g/m^2/s^{1/2}$)	1.6		0.2		0.4*	

* Measured on basalt rock.

rocks (granite, migmatite, basalt among others) with a quite smooth surface texture, and a porosity lightly higher than the granite.

Two fractions with similar particle size distribution were adopted with maximum aggregate sizes of 19 mm or 38 mm. Table 1 presents the characteristics of these aggregates including results of water absorption (24 h), density, abrasion resistance (Los Angeles) and strength. Tensile and compressive strengths were estimated from punctual loading tests performed on the particles of 19 mm size [12]. In addition, in the case of the granite and quartzite (crushed stones), drilled cores (100 × 200 mm) and sawn prisms (25 × 25 mm section) were obtained from blocks of the rock to measure the compressive and flexural strength respectively.

As a reference of the interface characteristics in concretes prepared with these aggregates, Table 1 also includes results of bond strength, measured on specimens composed of half rock and half mortar [13]. Rock surfaces were carefully sanded to obtain a surface texture similar to that of the respective crushed aggregates. It is possible to see that quartzitic rocks show the highest values due to their surface texture and absorption. In addition, it was tested a granitic rock with diamond sawn surface, not sanded, representing an aggregate with smoother surface texture and lower absorption. The bond strength of smooth granite surfaces were 5.1, 6.4 and 7.3 MPa for the matrix strength of 7.7, 8.5 and 10.8 MPa respectively. It is estimated that due to the texture of the river gravel particles, the bond strength of this aggregate must be higher than these values and smaller than the sanded granites ones.

In a complementary way, to contribute to the analysis of the influence of coarse aggregates characteristics on concrete transport properties, sorptivity tests were performed on different rocks. Small prisms of quartzite and granite of 25 × 25 mm section, lateral sealed and immersed 3 mm in water, were used. As expected the quartzite showed greater values than the granite (Table 1). In addition, similar tests were performed on samples of basalt considering that this type of rock is abundant in the used river gravel. The values of capacity and velocity of capillary absorption of the basalt are between the quartzitic and the granitic rocks.

2.2. Concretes

Six concretes, identified in accordance with the aggregate type and size, were prepared. Two coarse aggregate fractions were considered, 19 and 38 mm maximum size, obtaining the concretes Q19, Q38, G19, G38, R19 and R38. Their mixture proportions and properties are included in Table 2. Ordinary Portland cement was used. In all cases the water/cement ratio remains constant and equal to 0.50. The water content was reduced and the aggregate

Table 2
Concretes.

Concrete		Q19	Q38	G19	G38	R19	R38
Water	(kg/m^3)	180	165	173	164	164	147
Cement	(kg/m^3)	360	330	347	328	329	293
Fine aggregate	(kg/m^3)	825	805	850	805	870	845
Coarse aggregate	(kg/m^3)	900	1000	960	1075	1015	1110
Slump	(mm)	70	45	65	65	165	145
Compressive strength (1 year)	(MPa)	43.5	45.4	45.6	43.6	40.4	38.4
Modulus of elasticity (1 year)	(GPa)	37.2	37.7	40.6	41.3	41.5	39.5

content was lightly increased (near 20 L/m^3) when river gravel was used due to the shape and surface texture of the particles of this aggregate. As usual the coarse aggregate volume increases as the maximum size increases, in this case the difference between 19 and 38 mm fractions was near 40 L/m^3.

Cylinders of 150 × 300 mm were cast and cured in moist room during 90 days. After that, all specimens were stored inside the laboratory, protected from temperature and moisture extreme changes. Table 2 also shows the compressive strength and the modulus of elasticity measured at 1 year. Each result is the mean of four tests ranging the coefficients of variation between 2% and 8%.

2.3. Experimental program

All specimens remained in the same conditions in the laboratory (Temperature: 20 ± 10 °C. Relative humidity: 70 ± 10%). At the age of 10 years the cylinders were divided in three groups in order to analyze different damage levels. In the first group the mesostructural characteristics and the mechanical and transport properties were evaluated without performing any extra damage. In the other groups stronger damages were produced by means of high temperate exposure or load application. The different groups are:

Group D: there is some damage associated to the effects of drying shrinkage in moderate conditions (10 years in laboratory ambient).

Group T: to increase the damage level the specimens were exposed to high temperature. An electric oven with automatic control of the temperature was used, the temperature was raised at a rate of 100 °C/h until 500 °C. This temperature was kept for 1 h and then the specimens were cooled inside the oven. In this case the loss of water from the gel pores and the differences in the coefficients of thermal expansion of the aggregates and paste are the main causes of cracking. It must be noted that the damage level is lower than if the same procedure would have been applied in a younger concrete, because the specimens had already lost significant amount of moisture.

Group L: the specimens were loaded in compression up to 90% of their corresponding maximum capacity, maintaining the maximum load during 10 min. Complementarily, some specimens were only loaded up to 70% of their maximum capacity but they were only tested to air permeability (Group L*).

2.4. Test methods

Mesostructural analysis: the level of damage in each group was evaluated through a detailed survey of the crack pattern complemented by ultrasonic pulse velocity tests. The ultrasonic pulse velocity was measured on standard cylinders through direct transmission using a portable equipment with a 54 kHz transducer and a 0.1 μs resolution. To analyze the crack pattern, transversal cuts were done. They were firstly observed using a magnifying glass, then the cut surfaces were covered with a transparent film and the visible cracks and the aggregate areas higher than 5 mm, were marked. The films were scanned, and the obtained images were analyzed with an image-processing software. The length and density of the cracks and the density and total perimeter of the coarse aggregates were considered for the analysis.

Compression tests: uniaxial compression tests were performed on standard cylinders following the general guidelines of ASTM C39 and ASTM C 469 [14,15]. They were capped with a sulfur mortar. Three loading–unloading cycles, up to 40% of the maximum stress, were applied to determine the modulus of elasticity, after which the load was increased monotonically up to failure. A controlled closed-loop system was used, being the axial deformation the control signal.

Capillary absorption: these tests were performed on 50 mm slices cut from the cylinders. The lateral surfaces of the specimens were sealed with a water proof paint to avoid lateral losses and ensure a uniaxial-flow. The sawn surface was immersed in water (depth 3 mm) and the velocity (sorptivity) and the absorption capacity were calculated [16]. This test is particularly sensitive to the size of the connected pores.

The water permeability is a property that describes the fluid movement through the saturated pore structure of concrete under pressure. The next two tests were considered to evaluate this property. The same equipment was used in both cases and, as in the previous test, the specimens lateral surfaces were sealed with a waterproof paint to avoid water losses.

Water penetration under pressure: the general guidelines of CPC RILEM 13.1 [17] were followed. Samples of 150 mm thickness were used. A ring of 25 mm thickness was sealed at the contact face, though the water was applied through an area of 100 mm diameter. The pressure cycle consist in 0.1 MPa for 48 h, 0.3 MPa during the following 24 h and finally 0.7 MPa for 24 h; then the specimens were broken by splitting and the humid profile was recorded to obtain the water penetration depth.

Water permeability: to evaluate the coefficient of water permeability slices of 40 mm thickness were cut. In this case rings of 25 mm were sealed at the upper and lower faces, though the water was applied through an area of 100 mm diameter. The initial water pressure was 0.1 MPa, increasing until a stable flow was reached; the final pressure was in accordance with the level of damage. Major details are given in [11].

Air permeability: the Torrent equipment was used to measure the air permeability of concrete. It has a two-chamber vacuum cell and a regulator that balances the pressure in the inner (measuring) chamber and in the outer chamber. The cell was placed on the surface of 150 × 150 mm cylinders and a vacuum is created with the pump in both chambers. When the inner chamber system is insulated, the pressure in the inner chamber starts to increase, as air is drawn from the underlying concrete. The rate of pressure rise is directly related to the permeability of the concrete. The outer chamber acts as a "guard-ring", creating a controlled, unidirectional air flow into the inner chamber. The equipment gives the coefficient of permeability (kT) calculated on the basis of a theoretical model [18].

3. Test results

Fig. 1 shows the matrix-aggregate interfaces of the concretes of Group D. The photographs were taken from polished cuts with a stereomicroscope. It can be observed that in concrete Q the interfaces do not present discontinuities as it occurs in the other two cases. In concrete R there were found small cracks around the smoother surface of the aggregates and even thin cracks that run from the aggregates into the matrix.

Table 3 shows the mean values of density and perimeter of coarse aggregates and the crack density measured on sawn surfaces. The density of aggregates (surface of aggregate/surface of concrete) varies between 0.28 and 0.37 cm^2/cm^2 in the concretes with 19 mm maximum size and between 0.32 and 0.43 cm^2/cm^2 in the concretes with 38 mm maximum size. The highest values correspond to concretes R, as they have a greater volume of aggregates. Concretes incorporating 38 mm maximum size aggregates had the lowest perimeter length of aggregates (perimeter of aggregate/surface of concrete), as expected.

Fig. 2 shows the variation of the crack density in each concrete for Groups D, T and L. It can be seen that in Group D, only affected by drying, the lowest crack density corresponds to concretes Q, followed by G and R. In Group T, the crack density increases

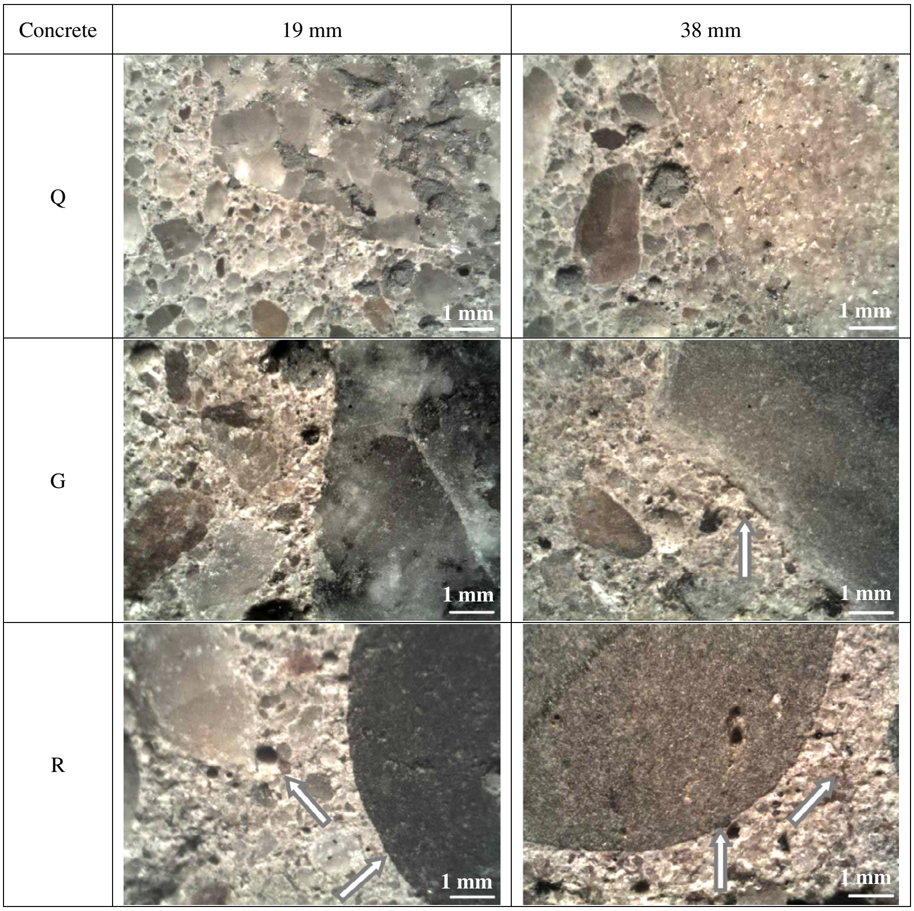

Fig. 1. Photographs of sawn and polished cuts taken with a stereomicroscope from specimens belong to Group D. The arrows show cracks and interface discontinuities.

Table 3
Analysis of coarse aggregates and cracks density on sawn surfaces.

Concrete	Group	Aggregates density (cm^2/cm^2)	Aggregates perimeter (cm/cm^2)	Cracks	
				cm/cm^2	N°/cm^2
Q19	D	0.31	1.68	0	0
	T			0.13	0.18
	L			0.07	0.09
Q38	D	0.32	1.40	0.02	0.04
	T			0.13	0.22
	L			0.07	0.08
G19	D	0.28	1.79	0.05	0.08
	T			0.14	0.28
	L			0.10	0.20
G38	D	0.35	1.49	0.06	0.11
	T			0.18	0.25
	L			0.16	0.22
R19	D	0.37	1.83	0.04	0.08
	T			0.22	0.36
	L			0.11	0.12
R38	D	0.43	1.36	0.11	0.09
	T			0.22	0.24
	L			0.12	0.14

markedly; again concretes R have the highest values. Regarding Group L, the lowest crack densities correspond to concretes Q and the highest to G38. In the case of load induced cracking, as the applied stress is very close to maximum stresses, a small difference in the load level reached in each specimen can modify its crack pattern. The shape of the aggregate particles also affects crack formation, the branching of cracking during loading is more important when irregular shape aggregates with rough surface are used. Then, when comparing concretes G and R, it can be expected to find higher number of cracks in concretes G. It is interesting to note that this does not happened in concretes Q, because they present better interfaces.

The coarse aggregate characteristics and the consequent interface properties modify the failure mechanism of concrete [4,6]. Fig. 3 shows the fracture surfaces of the specimens of Group D after compression tests. In concretes R the aggregates were debonded

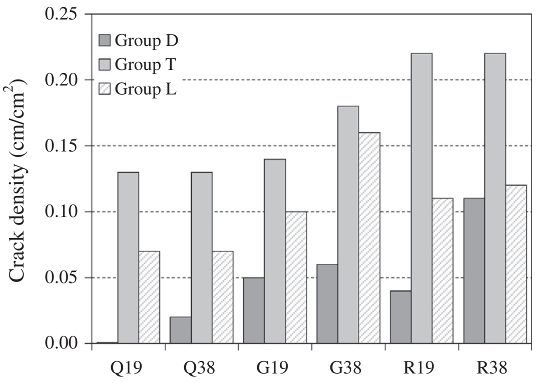

Fig. 2. Results of crack density in concretes with different coarse aggregates.

while in concretes Q all the aggregate particles were fractured; in concretes G both debonded and fractured aggregates can be seen.

Table 4 shows the results of compressive strength, elastic modulus and ultrasonic pulse velocity measured on Groups D and T. Each result corresponds to a mean of three tests. It also includes the relationships between the test results of Groups T and D. Due to the severe damage, the compressive strength in Group T decreased between 20% and 40% when compared with Group D. The reduction in the elastic modulus was greater and ranged between 60% and 70%. Concretes R were the most affected. All concretes of Group T showed similar decreases in ultrasonic pulse velocity which were near 40%.

Table 5 summarizes the results of transport properties corresponding to Groups D, T and L. Each value corresponds to a mean of five specimens in the case of water penetration and capillary absorption tests, and four specimens in the case of water and air permeability tests. Compared to Group D significant increases in water permeability were observed in Group T, while in Group L there only appeared light increments. The same as the water permeability, the air permeability showed a high increment when comparing Groups T and D. It is important to indicate that the air permeability test [18] can be used to evaluate undamaged concrete; for that reason, in some cases, measurements were not possible as they were out of range. In Group L* (loaded up to 70% of compressive strength) the air permeability also increased lightly respect to Group D following the concretes the same tendency as in Group L.

In Group D, although the concrete strength range between 31.5 and 42.8 MPa, the water penetration depths were very high; the values clearly exceed 100 mm making evident the presence of significant microcracking. In Groups T and L, as they are more damaged, water penetration tests were not performed.

Table 4
Compressive strength (*f*′c), Modulus of elasticity (*E*), and Ultrasonic pulse velocity (UPV) measured on Groups D and T.

Concrete	Group	Q19	Q38	G19	G38	R19	R38
f′c (MPa)	D	42.7	42.8	42.5	37.1	36.4	31.5
	T	27.7	28.0	32.0	29.7	22.1	20.8
E (GPa)	D	33.4	35.6	35.7	35.3	36.2	34.6
	T	14.1	14.3	15.1	14.6	11.6	12.7
UPV (km/s)	D	4.09	4.19	4.21	4.31	4.28	4.30
	T	2.34	2.45	2.55	2.63	2.54	2.45
f′c (MPa)	T/D	0.65	0.65	0.75	0.80	0.61	0.66
E (GPa)	T/D	0.42	0.40	0.42	0.41	0.32	0.37
UPV (km/s)	T/D	0.57	0.58	0.61	0.61	0.59	0.57

Regarding the capillary absorption tests, it appears that the differences between the groups are not so marked being higher in Group T. In each group, the values were very similar independently of the aggregate type or size. Table 5 shows a light decrease in the capillary absorption capacity in the concretes of Group L, which can be related to some consolidation of the paste during loading.

4. Discussion

The changes in the properties of old concretes produced by the type and size of coarse aggregates when different damage levels are present, as well as changes in the relationships between mechanical and transport properties, will be discussed in this section. It must be remembered that the characteristics of the matrix phase were the same in all concretes, thus the differences in the internal structure of concretes were mainly produced at the interfaces, as a function of the used coarse aggregates. Three internal damage levels were considered: Group D, where there is only small cracking mainly localized at the interfaces, which is representative of conditions usually found in concrete structures; Group T, where both the interfaces and the mortar matrix are strongly damaged due to the exposure to high temperatures; and Group L, an intermediate condition, with cracks induced by loading.

At the age of 1 year (see Table 2) all concretes had compressive strengths close to 40 MPa and differences in stiffness in accordance with the type of coarse aggregate used. Concretes R showed the lowest strengths while the lowest values of the modulus of elasticity correspond to the quartzitic crushed stone.

Fig. 4 presents the results of the modulus of elasticity as a function of the compressive strength for Groups D and T; it also includes the results obtained at 1 year. In this way the effect of the

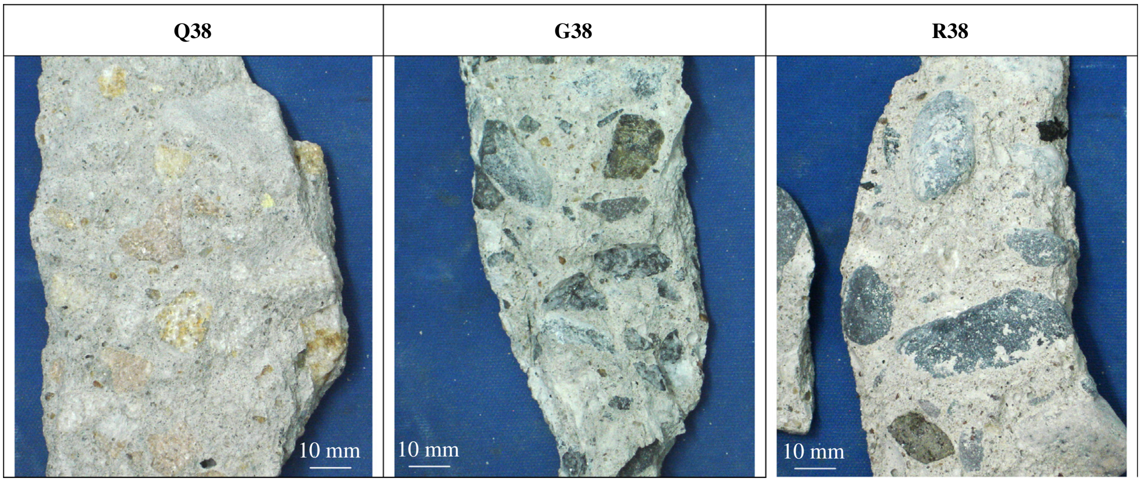

Fig. 3. Visual aspect of the interfaces after compression tests.

Table 5
Transport properties.

Group	Concrete	Capillary absorption		Water permeability coefficient ($\times 10^{-12}$ m/s)	Coefficient of air permeability kT ($\times 10^{-16}$ m^2)		Water penetration depth (mm)
		Sorptivity (g/m^2/s$^{1/2}$)	Capacity (g/m^2)				
D	Q19	10.7	4140	1.8	2.3		138
	Q38	9.3	3770	2.6	2.4		127
	G19	14.0	4220	1.2	0.9		128
	G38	11.3	3870	6.6	1.3		148
	R19	11.1	3990	1.1	1.7		119
	R38	10.9	3920	9.4	2.0		131
T	Q19	16.8	4620	980	+		nm
	Q38	20.0	4080	1210	+		nm
	G19	21.1	4530	480	35.2		nm
	G38	20.9	4010	260	50.4		nm
	R19	16.8	4260	1000	52.0		nm
	R38	26.7	4660	1160	+		nm
L	Q19	10.5	3780	8.6	2.4*	2.3	nm
	Q38	12.6	3530	11.1	2.4*	2.9	nm
	G19	13.0	3540	7.2	1.3*	1.7	nm
	G38	13.7	3680	15.6	1.8*	1.6	nm
L	R19	10.5	3730	7.7	1.8*	3.4	nm
	R38	11.5	3590	10.8	2.4*	4.0	nm

+: Out of range.
nm: Not measured.
* Specimens loaded up to 70% of compressive strength.

aggregate on both parameters for each damage level can be appreciated. Considering the aggregate type, it appears in the three groups that for concretes G and R the compressive strength was higher when a maximum size of 19 mm was used; this effect was more evident in Group D. On the contrary, concretes incorporating quartzitic stone (Q) do not show decreases of strength when a larger aggregate was used. After 10 years the compressive strength decreased up to 20%, being the concretes R which suffered the largest reductions, mainly the specimens prepared with 38 mm coarse aggregates. It is important to remark that this does not occur in concretes Q that maintained the strength level measured at 1 year. After 10 years (Group D) the modulus of elasticity decreased between 6% and 15%, being the concretes G and R the most damaged. The decreases in the mechanical properties of Group D can be attributed to microcracking caused by drying. Concretes Q, with the best interface bond and with a better elastic compatibility between aggregate particles (lower stiffness [4]) and mortar are the less affected (Table 1). The effects of aggregate size on both the strength and the modulus of elasticity depend on the interface characteristics which are affected by the aggregate shape, surface texture and stiffness.

Comparing Groups T and D, when more severe damage was produced, the compressive strength decreased between 30% and 50%, meanwhile the reduction in the elastic modulus was greater, almost a 70% (see Table 4). Again concretes R with the smoother interfaces and round shapes were the most affected while concretes Q were the less damaged (lower stiffness and the best interfaces). As it is well known the elastic modulus is more affected than the compressive strength by the presence of cracks; the reductions in the concrete stiffness are a typical behavior observed in damaged concretes [19]. It is interesting to note that when there is very extensive matrix damage as in Group T, there is not a major effect on the mechanical properties associated with the coarse aggregate size.

Fig. 5 presents the variation of the mechanical properties, expressed as relative values of the results obtained at 1 year, with the crack density. There is a clear relationship between crack density and the reduction in compressive strength; in the case of the elastic modulus the reductions are even higher with a drastic decrease in Group T. Regarding the effect of coarse aggregate type it is clearly seen that the greater reductions correspond to the river gravel.

Regarding the effect of coarse aggregate on the transport properties, it must be remembered that the aggregates are less permeable than the paste and force water to flow around them. When the aggregate size increases, added to the increase in the porosity and the thickness of the interfaces [7], the water path becomes less tortuous [20], leading to increments in permeability.

To analyze the effect of the coarse aggregate type when different transport mechanisms are involved, Fig. 6 compares the coefficient of water permeability and the rate of capillary absorption obtained in Group D. Meanwhile the coefficient of permeability increases with the aggregate size, mainly in the case of concretes R, the differences in sorptivity are not significant, showing concrete G19 the highest values. Table 5 shows that the effect of aggregate type and size is not so evident when water penetration tests are considered; only an increase in penetration depth with the coarse aggregate size in concretes G and R was noticed. However it must be observed that the penetration depths were very high, they significantly exceed the values usually found in 28 days concretes with these strength levels. In all groups the coefficient of air permeability was higher in concretes prepared with the highest aggregate size; nevertheless the differences between them were too small.

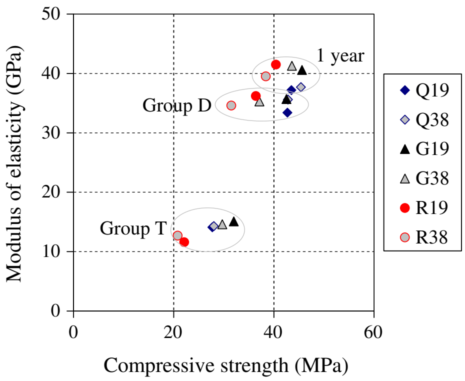

Fig. 4. Modulus of elasticity vs. compressive strength.

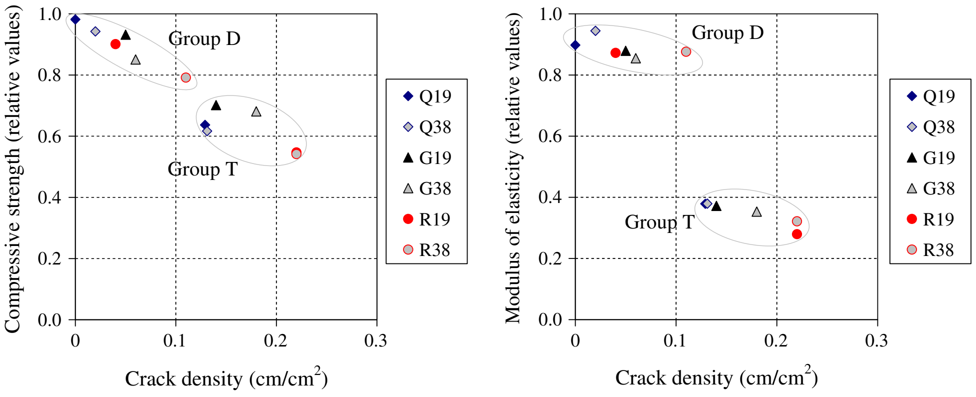

Fig. 5. Variation of compressive strength and modulus of elasticity with the crack density.

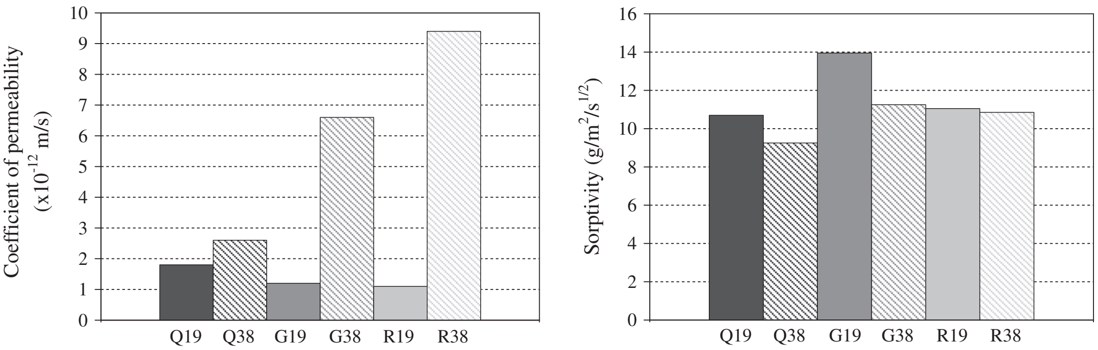

Fig. 6. Effect of the coarse aggregate on the transport properties (Group D). Left: coefficient of water permeability, Right: sorptivity.

Regarding the effect of coarse aggregate on capillary tests, it was very interesting to note that although there are significant differences between each rock, this does not occur in concrete. Table 1 shows that the highest values both in capacity and velocity of capillary absorption (940 g/m^2 and 1.6 g/m^2/s$^{1/2}$) correspond to the quartzitic rocks, followed by the basalt (200 g/m^2 and 0.4 g/m^2/s$^{1/2}$), meanwhile the granitic rocks showed the lowest values (100 g/m^2 and 0.2 g/m^2/s$^{1/2}$). These differences in the capillary absorption tests between the rocks and the concretes highlight the influence of the interfaces on the transport properties of concrete.

As in Group D the damage is mainly localized at the interfaces, Fig. 7 plots the variation of the permeability coefficient with the total coarse aggregate perimeter. This parameter is representative of the interfaces length and it increases when the aggregate size decreases. It can be seen that the coefficient of permeability decreases as the aggregate perimeter increases, especially in concretes G and R. This can be justified considering that although the total length of the interfaces is higher, as the aggregates are smaller, each interface is smaller and then it is less porous and also less affected by drying shrinkage. It is very interesting to observe the behavior of concretes Q; although these aggregates are more permeable, their interfaces are better (Table 1), and then the changes in the aggregates perimeter are not so influential on the permeability as in concretes G and R.

In Group T where the damage is higher and the matrix is also affected [19,21,22] there was not a clear effect of the type and size of the aggregate (see Table 5). However, when comparing with Group D, all concretes show significant increments in permeability.

As a summary, Fig. 8 shows the variation of the sorptivity and the coefficient of permeability as a function of the crack density. The transport properties are clearly affected by the presence of cracks; however the magnitudes of the changes are quite different according to the transport mechanisms involved. It can be seen that while the permeability drastically grew with the crack density the increase of sorptivity is not so important.

Finally, Fig. 9 represents the results of water and air permeability coefficients, capillary absorption capacity and sorptivity as a function of the compressive strength of concretes. It is clearly seen that although both of them may show a similar tendency, strength and transport properties are not always strictly related. There can be great differences in the values of transport properties corresponding to concretes of similar strength (all of them prepared with the same water/cement ratio). The changes in concrete

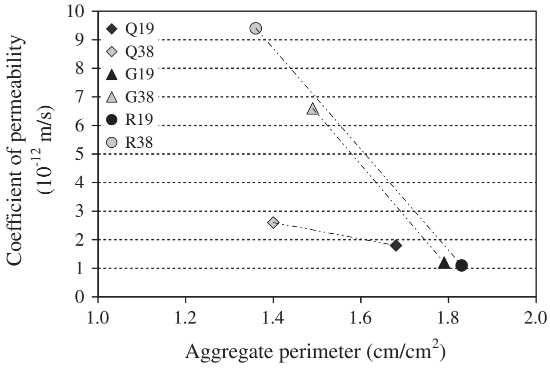

Fig. 7. Variation of the coefficient of permeability with the coarse aggregate perimeter (Group D).

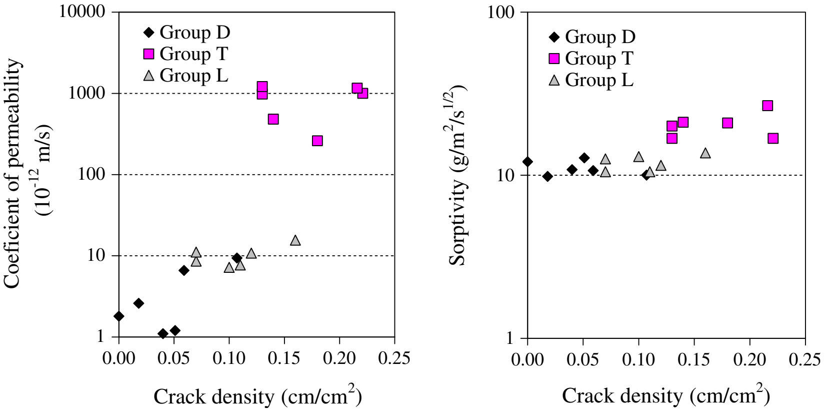

Fig. 8. Variation of the sorptivity and the coefficient of permeability with the crack density in Groups D, T and L.

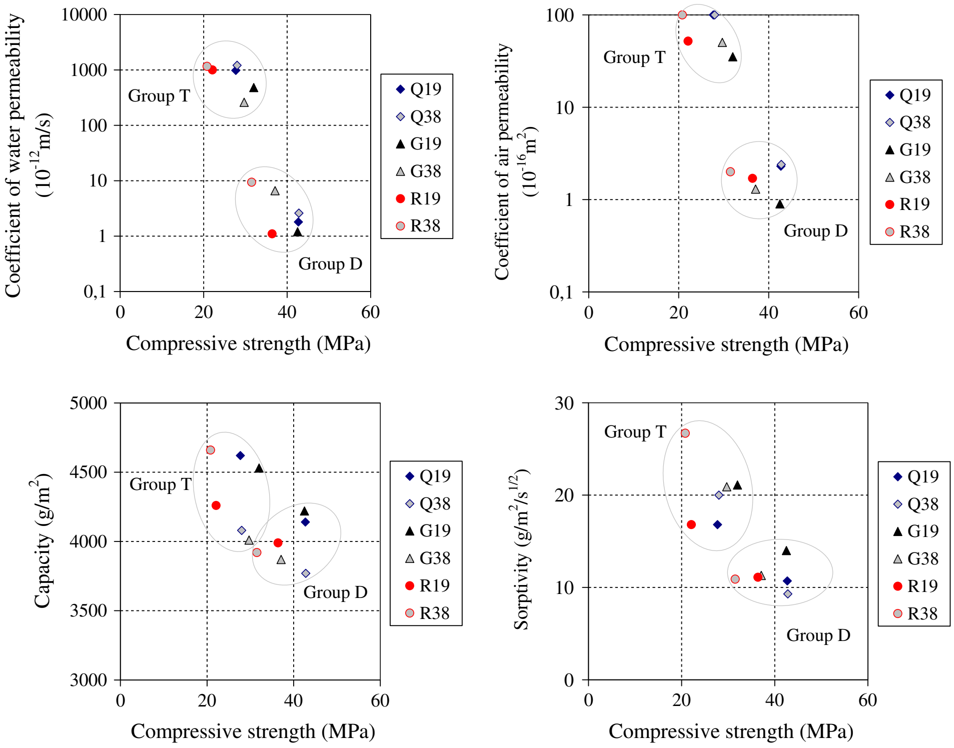

Fig. 9. Relationship between the transport properties and the compressive strength of concretes. Groups D and T.

internal structure affect mechanical and transport properties in a different way.

5. Conclusions

This paper evaluates the properties of 40 MPa compressive strength concretes, prepared with different coarse aggregates, exposed during 10 years to moderate environmental conditions. In addition the residual properties of the same concretes after high temperature exposure or load-induced cracking are considered in the analysis. The aggregates used were granitic (G) and quartzitic (Q) crushed stones and a natural river gravel (R) with 19 and 38 mm maximum size. The main conclusions are shown below:

The compressive strength decreased after 10 years exposed to laboratory ambient, being the concrete with river gravel and 38 mm maximum size which suffered the largest reductions. On the contrary, the concretes prepared with quartzitic stone maintained the initial strength level. As expected the modulus of elasticity also decreased, being the concretes G and R the most damaged. The minor deterioration of concretes Q is associated to the best interface bond and elastic compatibility between the aggregates and the matrix. When the same concretes were severely damaged, by the exposure to high temperature, the mechanical properties strongly decreased; again the concretes R were the most affected. In very damaged concretes the coarse aggregate size did not seem to have a major incidence.

Considering the transport properties, the water permeability coefficient increased as the aggregate size increased. The effect of aggregate size was smaller in concrete Q; this is related to the better interfaces. Sorptivity and water penetration tests did not show any effect of the aggregate type or size. In concretes damaged by high temperature the water permeability was more affected than the capillary absorption. The level of damage induced by high temperature overlapped the effects of coarse aggregate, being the granite the less affected. The same as the water permeability, the air permeability showed a high increment when great damage took place. When load induced cracking was present in concrete, the water and air permeability suffered a light increase.

Considering the relationships between transport properties and damage level, it was found that the water permeability drastically grew with the crack density while the increase of sorptivity with the crack density was not so important.

The grade of damage produced by drying, high temperature or loads is affected by the quality of the interfaces and stiffness of the aggregates; however when the extent of matrix microcracks or cracks is important the coarse aggregate acquires a secondary role. Comparing the different tests studied, water permeability seems to be the transport mechanism most sensitive to the type and size of coarse aggregate.

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