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Use of porous ceramic waste aggregates for internal curing of high-performance concrete

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ABSTRACT

Internal curing has become extensively used to reduce autogenous shrinkage and consequently mitigate the high risk of early age cracking of high-performance concrete (HPC). This paper investigates the efficiency of internal wet curing provided by a new type of aggregate, "recycled waste porous ceramic coarse aggregates" (PCCA). Six different silica fume HPCs with and without the PCCA are examined with respect to measured physical and mechanical property development. Four different replacement proportions of normal weight coarse aggregate (NCA) by the PCCA have been evaluated. The results have shown a high effectiveness of the PCCA for internal curing purposes, to drastically reduce and even to completely eliminate autogenous shrinkage of HPC prepared with a very low water/binder ratio (w/b) of 0.15. It has been found that the incorporation of 40% of the PCCA leads to a non-shrinking HPC that results in an insignificant internal stress accompanied by a significant increase of the compressive strength. It should be noted that for the different proportions of the PCCA incorporated no decrease of the compressive strength has been observed at either early or later ages, as is the case with some conventional lightweight aggregates.

1. Introduction

Over the last decades, HPC with a low w/b has become widely used and research works on this matter have increased tremendously. Their high strength and durability performance were considered as key issues for structural use under severe conditions. However, from the practical point of view and laboratory investigations, it has been proven that HPC is very sensitive to the risk of early age cracking unless special precautions are taken. One of the specific requirements is the curing practice [1]. A proper curing is crucial for the performance of concrete and should be considered as a key factor to achieve durable HPC. This type of concrete with very low w/b contains an insufficient amount of water to maintain water-filled capillary pores (saturation state of capillary pores), needed to both sustain continuous cement hydration and pozzolanic reaction, and to consequently prevent self-desiccation phenomena.

Since autogenous shrinkage is the dominant volume change for HPC, it is well recognized that the high risk of early age cracking of HPC is attributed to the large magnitude of early age autogenous shrinkage caused by internal drying of the concrete during binder hydration reactions. On the other hand, as autogenous shrinkage is intimately related to the self-desiccation phenomena and the consumption of water by the cement hydration, the formation of menisci in the pore solution will result in the development of autogenous strains and stresses within the solid hydrating cement paste.

Over the years, several methods have been proposed to mitigate autogenous shrinkage and the internal stress that might be induced. Expansive additives (EXA) based on calcium sulfoaluminate or free lime [2,3], drying shrinkage-reducing admixtures (SRA) [3–5] super-absorbent polymer particles inclusions [6], as well as high belite or low heat Portland cement [2,3] have been successfully and extensively used in mitigating shrinkage. However, the use of sulfoaluminate based expansive additives might have a detrimental effect regarding the possibility of delayed ettringite formation (DEF), especially when used in massive concrete elements. In fact, the expansive agent used in massive concrete cannot give full play to its shrinkage compensating effect when the curing temperature exceeds 70 °C. Depending on the type of binder used and the size of the concrete element, the temperature rise in the core of massive concrete may reach 65 °C [7]; even around 90 °C was recorded in the case of the Shanghai Jinmao building in china [8]. Such a high temperature in a massive concrete containing an expansive agent of the sulfoaluminate-type could result in DEF, as reported by many authors [9–12]. Therefore, the use of EXA sulfoaluminate-type in concrete is subjected to several limitations and precautions must be taken to avoid any damaging effect. Recently, Yan et al. [13] have confirmed the detection of DEF in shrinkage compensating concrete subjected to temperatures higher than 70 °C.

Furthermore, in terms of durability of concrete, it has been proven that internal water curing, called also “autogenous curing,” is the safest and most efficient method to reduce autogenous shrinkage

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Table 1
Physical properties and chemical compositions of cements and SF used.

Composition and properties	OPC	SFLC	SF
Chemical composition (%)			
SiO_2	20.84		94.1
Al_2O_3	5.25		0.6
Fe_2O_3	2.97		0.9
CaO	63.88		0.0
MgO	1.38	0.76	0.9
SO_3	2.12	2.23	0.2
Na_2O	0.23	–	0.35
K_2O	0.34	0.51	0.63
Cl	0.004	0.009	0.04
LOI	1.64	1.04	1.3
Mineralogical Composition (%)			
C_3S	56	30	
C_2S	25	49	
C_3A	10	5	
C_4AF	6	10	
Physical properties			
Specific gravity	3.16	3.08	2.24
Fineness m^2/kg	338	581	19 000

compared to the use of expansive additives in concrete. The idea that self-desiccation can be counteracted by partial replacement of normal aggregate (NA) by pre-saturated lightweight aggregate (LWA) was conceived and demonstrated by various authors [6,14–18].

Aïtcin [19] has expected that HPC should be cured with external water for at least 7 days in order to minimize autogenous shrinkage and the risk of early age cracking. External water curing that supplies additional moisture is one of the most conventional and well known applied curing methods and has revealed a high efficiency in mitigating autogenous shrinkage of small size concrete elements. However, once the capillary pores depercolate, it will be more difficult to provide adequate external water curing, thus reinforcing the need for internal curing [20]. Both external water curing and many other externally applied curing methods (such as water ponding, water spraying, wet burlap, plastic foiling,…etc.) are unable to prevent the reduction of internal relative humidity due to capillary water consumption during the cement hydration reactions which leads to self-desiccation phenomena. Therefore, and as mentioned above, internal water curing is considered as the most effective method for reducing autogenous shrinkage and consequently, the induced capillary stresses. The concept of internal wet curing is based on the use of internal reservoirs providing a source of curing to the cement paste to offset self-desiccation phenomena. One procedure that has been extensively investigated consist of incorporation of pre-saturated LWA into the concrete mixture, which serves as a water reservoir that gradually releases water to replace that consumed during hydration reactions. Previous results have shown that the use of LWA for internal curing could successfully mitigate or completely eliminate autogenous shrinkage of HPC [21–28]. It was suggested that internal wet curing applications will be especially useful in blended cements containing SF or others mineral admixtures where the water supply might sustain the later age pozzolanic reaction between portlandite and the mineral admixtures added [20].

The efficiency of an internal curing system is strongly related to both the content and the parameters of LWA used, such as water absorption, pore structure and grain size distribution, open to closed porosity ratio, as well as mechanical properties. The paste-aggregate proximity is a decisive factor determining the distance which the internal curing water should readily penetrate. Some authors have reported that fine lightweight aggregate were found to be more effective in distributing available moisture for internal curing than the coarse lightweight aggregate [28,29]. While other authors [25] have estimated that the pore size plays a more significant role in the process of internal curing than the grain size. The dosage of LWA depends mainly on having a sufficient amount of internal curing water to introduce into the cement matrix. It has been considered that a low content of LWA around 6% of cement weight could totally eliminate autogenous shrinkage of HPC [16,25,28]. Conversely, Bentur et al. [24] have estimated that 25% of fine LWA as replacement of NWA could be effective in eliminating all the autogenous shrinkage in HPC.

In fact and as pointed out above, both conventional LWA and anti-shrinkage agents are subject to certain limitations with regards to practical use for shrinkage compensating concrete. On one hand, it has been proven that a high content of conventional LWA may be required to completely eliminate autogenous shrinkage which results in a significant decrease of compressive strength that affects the performance of such type of concrete and possibly negates its benefits. On the other hand, the use of a sufficient amount of SRA and EXA may increase considerably the total cost of concrete. The center of excellence for airport technology (CEAT) [30] has estimated that the use of SRA in a sufficient amount could increase the final cost by approximately 16%. It can be expected that roughly the same cost increases might be generated when using EXA in HPC. Therefore, the high cost of anti-shrinkage agents (SRA and EXA), the growing risk of DEF in case of massive concrete elements or over dosage of the EXA, and the possible decrease of the compressive strength induced by the incorporation of conventional LWA could limit the use of such types of additives in HPC structural elements and increase the demand for alternative materials.

Nowadays, the use of by-products in cement-based materials has become a common practice [31–36] and considerable research work has been done. However, most of these studies focused mainly on the use of by-products as mineral admixtures, recycled normal aggregates or waste fibres as reinforcement. In the current investigation, a new type of recycled waste ceramic aggregate is incorporated as a partial

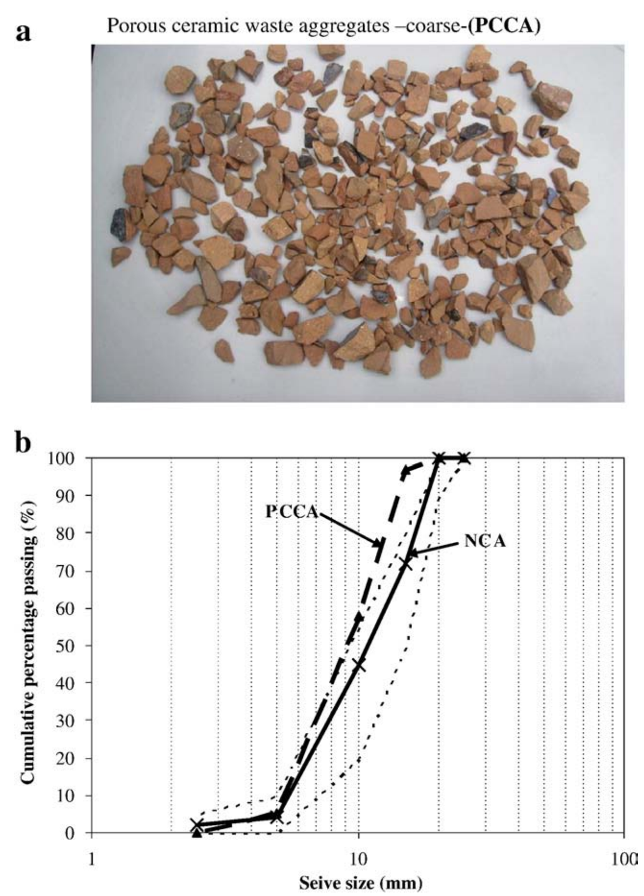

Fig. 1. Waste porous ceramic coarse aggregate: a) view of the PCCA, b) grain size distribution.

Table 2
Physical properties of the aggregates used.

Type of aggregate	NCA	CLWA	PCCA	NFA
Specific gravity	2.92	1.27	2.27	2.62
Water absorption capacity (%)	0.88	12.2–22.3	9.31	2.41
Fineness modulus	6.51	6.47	6.66	3.21
Crushing rate	7.86	37	21.4	–

replacement of NCA as a water-entraining agent used for internal wet curing in order to mitigate autogenous shrinkage of HPC.

2. Experimental

2.1. Materials

Ordinary Portland cement (OPC) equivalent to ASTM Type I in combination with 10% of silica fume (SF) added as a partial replacement and a premixed binary binder based on a low heat high belite cement (SFLC) containing 10% of SF were used in this investigation. The chemical compositions and physical properties of the cements and SF are shown in Table 1. Crushed sandstone with a maximum nominal size of 5 mm was used as normal fine aggregate (NFA) and crushed diabase with a maximum size of 15 mm was employed as normal coarse aggregate (NCA). A single fraction of a new type of recycled crushed porous ceramic coarse aggregate (PCCA) recovered from the waste of a local ceramic production plant was used as an internal water curing system (Fig. 1a). Table 2 summarizes the main characteristics of this type of porous aggregate compared to both the NCA and the conventional lightweight coarse aggregate (CLWA) that is most readily available in the Japanese market and used for internal wet curing purposes. The grain size distribution of the PCCA used is presented in Fig. 1b. In order to evaluate the crush resistance of aggregates, especially the PCCA, crush test was carried out in accordance with the JIS (Japan industrial standard). The impact value is found by dropping a standard hammer onto a sample of aggregate and measuring the weight of the fines resulting from the impact, therefore the lower the impact value, the tougher and stronger the aggregate. The impact value (Table 2) gives a relative measure of the resistance of an aggregate to sudden shock or impact. Both fine and coarse aggregate (NCA and PCCA) were used in saturated surface-dry conditions (SSD). A polycarboxylate-based superplasticizer (SP) having a specific gravity of 1.05 was used to obtain the target slump.

2.2. Concrete mixtures

Six different blended cement HPC mixtures were investigated in the present study using a single very low w/(c+sf) or w/b of 0.15. HPC mixtures with and without internal water curing were proportioned (Table 3). Two control mixtures were made without internal curing and four mixtures containing the PCCA for internal water curing. Four different proportions (10, 20, 30 and 40%) by volume were selected as partial replacement of the NCA by the PCCA. Labelling notations used for all mixtures investigated in this study are those indicated in the material section.

All concrete mixtures were prepared in a laboratory mixer using the same mixing procedure. Fresh concrete properties (temperature of concrete, air content and slump) were determined immediately after mixing sequence and before concrete specimens casting. The target slump for all concrete mixtures investigated was fixed at around 500 ± 50 mm and the air content ranged generally from 1.5 to 2.5%.

While binary concrete made with low heat belite cement is the reference concrete mixture regarding the effect of internal water curing provided by the PCCA addition, a second control mixture based on Portland cement with 10% of SF was also used in the current study.

As w/b of HPC is the major factor which greatly affects both the ultimate and the development of autogenous shrinkage, the choice of its value is decisive. On the one hand, w/b is determined by the strength and durability requirements, and on the other hand, autogenous shrinkage development. Therefore, selecting additives as well as w/b, the balance between strength development and autogenous shrinkage reduction should be considered. In the current study, and in order to demonstrate the results that might be obtained using this new type of porous aggregate for a large range of w/b values, a single very low w/b of 0.15 has been chosen. Efficiency of the internal water curing obtained under such severe conditions using the PCCA might be improved for higher w/b.

2.3. Specimen preparation

For each concrete type, all concrete specimens were prepared from the same concrete batch. Immediately after concrete casting, all specimens were covered with a plastic waterproof sheet and wet fabrics to avoid early water evaporation during the first hours. The concrete specimens were kept in their moulds in a controlled climate chamber at 20 ± 1 °C and 60 ± 2% of relative humidity (RH) until 24 h and then were demouled and sealed with two layers of aluminum tape to prevent any moisture loss or hygrometric exchange with the surrounding environment throughout the complete testing period.

The compressive and splitting tensile strengths, and Young's modulus were measured on three cylindrical samples measuring 100 mm × 200 mm for compressive tests and Young's modulus measurement, and 150 mm × 200 mm for the splitting tensile strength tests. Prisms measuring 100 mm × 100 mm × 400 mm and 100 mm × 100 mm × 1400 mm were used for autogenous shrinkage strains and stresses measurements, respectively. Both cylinders and prisms samples were cast in steel formworks and kept in sealed conditions under controlled temperature and relative humidity until the end of the tests.

2.4. Testing methods

For all concrete mixtures, two types of tests were performed: mechanical tests, and strains and stress development measurements. Autogenous shrinkage strain measurement was conducted using vibrating wire embedded strain gauges placed horizontally in the centre of the mould. Specimens were connected to a data acquisition system which is recorded to a computer. In addition to the strain measurements, this type of gauge is also able to record the temperature change. Strains and temperature measurements were started within few minutes after the concrete placement in the moulds to allow volumetric change recording during the earliest phases of cement hydration. In order to ensure continuous measurements, readings for both temperature and strains were taken at 10 min intervals for 28 days.

Throughout the whole measurement period, the specimens were kept sealed under the same conditions (T° and RH) mentioned above. In this study, measurement of both autogenous shrinkage strains and

Table 3
Mixture proportions and fresh properties of concretes mixtures investigated.

Components	Mix designation					
kg/m^3	NC	PC0	PC10	PC20	PC30	PC40
Cement	924.4	–				
SFLC	–	1033	1033	1033	1033	1033
SF	108.9	–	–	–	–	–
Water	155	155	155	155	155	155
NCA	944	944	850	755	661	566
PCCA	0	0	73	147	220	294
Fine aggregate	435	435	435	435	435	435
AFA* (g/m^3)	103.3	20.7	20.7	20.7	20.7	20.7
SP	36.17	25.83	25.83	26.87	25.83	23.76
Slump (mm)	450	600	550	615	530	590
Air (%)	2.5	1.8	2.7	2.2	1.6	1.9

*AFA: Antifoaming agent.

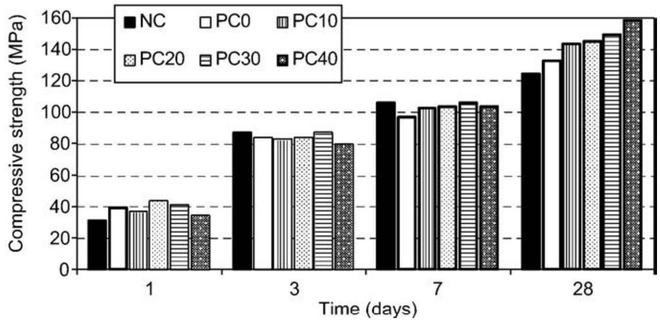

Fig. 2. Effect of the addition of the PCCA on compressive strength development.

stresses were made on two replicate specimens and the mean value was reported. It should be noted that the measurements have shown a good concordance and generally, a quite good similarity was observed between the recoded data of the two specimens tested. Concrete cylinders compressive strengths were carried out on three replicate specimens at the ages of 1, 3, 7 and 28 days of sealed curing.

As the binder used in the current study is a high belite low heat cement, it is interesting to mention that only a moderate heat was realized during the binder hydration reactions and thus, for all concrete mixtures investigated, temperature generally varied between 20 and 24.5 °C as the maximum value reached during the first 24 h and tended to stabilize beyond 1 day.

2.4.1. Stress measurement

A specimen size of 100 mm × 100 mm × 1400 mm with reinforcing bar was used for stress measurement. The loading system uses a preset degree of restraint by transferring the axial force to the concrete specimen through continuous embedded reinforcing bars, which somewhat simulates a reinforced concrete structure. Reinforcement bar diameter of 16 mm was embedded in the centre of the restrained concrete specimen. The axial force was measured using two strain gauges placed longitudinally at the centre of the reinforcing bar. The concrete temperature was measured on each specimen at the centre of the specimen using embedded thermocouples. This temperature was assumed to be uniform in the longitudinal direction over the central portion of the specimen where the strain gauges were placed. This proposed testing procedure for stress measurement induced by shrinkage was designed to offer partial restraint to the concrete specimen in order to simulate restrained conditions similar to those that might be found in real reinforced concrete structures.

The restrained stress development in concrete at the extreme bottom bar due to the restraint of reinforcement was determined using the Eq. (1). This equation is derived from the equilibrium of the forces between concrete and reinforcement as well as Navier's assumption. The stress is considered to be positive in compression and negative in tension.

$$\sigma_c = \frac{P_s}{A_c} \quad \text{and } P_s = A_s E_s \varepsilon_s \tag{1}$$

where, σ_c = stress on the extreme bottom fiber, P_s = the axial force in reinforcement, A_c = cross-section area of concrete, A_s = cross-section area of reinforcement, E_s = Young's modulus of reinforcement, ε_s = measured strains in reinforcement.

3. Results and discussion

3.1. Mechanical performance

3.1.1. Compressive strength

Compressive strength is considered as the most important mechanical characteristic of cement-based materials, especially HPC. The partial substitution of NCA by the PCCA could affect the compressive strength development over time depending on their characteristics. The average value of the compressive strength results up to 28 days for both the references and the internal cured concrete mixtures investigated are given in Fig. 2. In general, a good concordance between the three values of the cylindrical specimens tested on compressive strength was observed; their standard deviation ranged from 0.3 to 3.2 MPa.

It can be seen that compressive strength development has shown two different behavior modes and no significant effect of the addition of the PCCA has been observed at early age. However, beyond 7 days, the compressive strength of the internally cured mixtures starts to overcome that of the reference mix (PC0). While at early age (until 3 days) the effect of internal water curing provided by the PCCA is not noticeable and only a minor decrease of the compressive strength (3 to 4 MPa) was observed with a few mixtures, the contribution of the PCCA can be well identified at later ages. This slight decrease of the compressive strength for concrete mixtures containing the PCCA may be explained by the fact that at early ages, the cement paste is still relatively weak and has not yet developed a sufficient resistance, and the strength of the PCCA skeleton is lower than that of the NCA, as the crushing rate (Table 2) indicates.

At later ages, the entrained water contained in the pore system of the PCCA supplies additional water to produce further hydration products between 7 and 28 days. The results have shown that the gain of the compressive strength during this period of time is proportional to the content of the PCCA in the concrete mixture. Increasing the PCCA content leads to an increase of the gain of the compressive strength compared to that attained by the reference mix as illustrated in Fig. 3. Indeed, the 28-day compressive strength of the internally cured concretes containing the PCCA overcomes largely those of both the NC and the PC0 concrete mixtures. The highest compressive strength value of 158 MPa was reached at 28 days by the PC40 mix. This represents around a 20% gain compared to that of the reference concrete; while the PC10 mixture produces the lowest increase of the compressive strength by the order of 9%. The enhancement of the compressive strength is mainly attributed to the improvement of hydration processes by the internal water curing provided by the addition of the PCCA. In fact, the water supply entrained by the PCCA contributes to the formation and the growth of additional C–S–H into the capillary pores. Its refinement, filling, and transformation of coarse capillary pores into smaller ones lead to the observed compressive strength improvement. The compressive strength enhancement achieved by the incorporation of the PCCA compared to the reference mixtures is provided in Fig. 3. On the contrary, previous studies have shown that the use of conventional LWA leads to a significant decrease of the compressive strength at both early and later ages. Results obtained by some authors [24,28] indicate that the incorporation of LWA decreases the early ages compressive strength up to 7 days and the 28-day strength was close to that of the reference mix. Durán-Herrera et al. [37] have observed a decrease of 12% of compressive

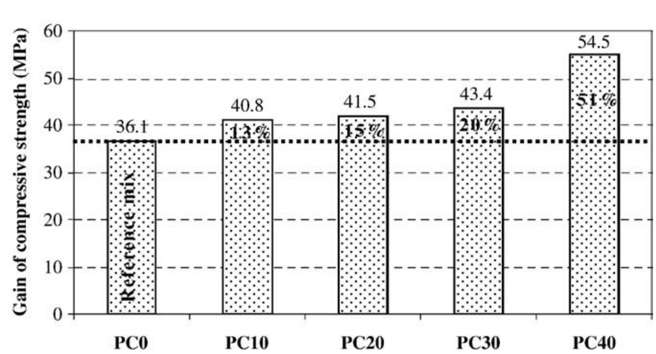

Fig. 3. Gain of compressive strength between 7 and 28 days for mixtures with the PCCA compared to the control mixture.

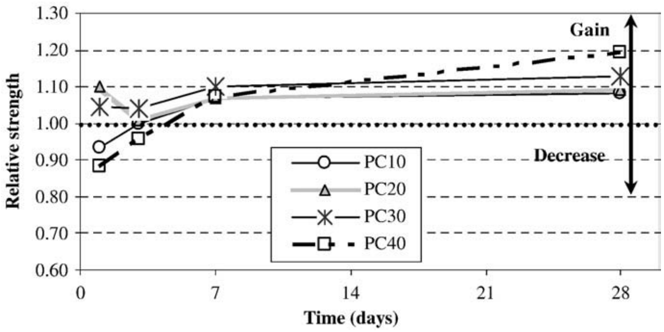

Fig. 4. Effect of the PCCA inclusion on relative strength of internally water cured mixtures.

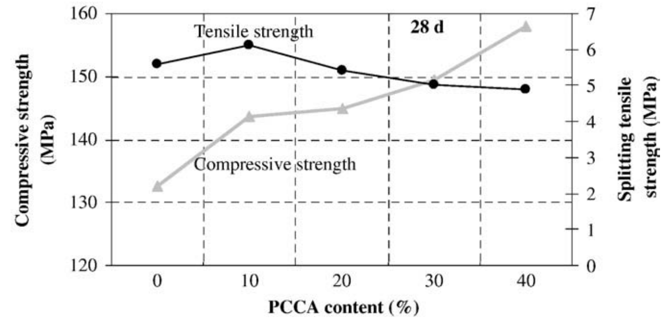

Fig. 6. The 28-day compressive and splitting tensile strengths development versus PCCA proportions.

strength for the internally cured concrete up to 7 days while no significant effect was found at later ages. Bentz [20] has found that mortars internally cured exhibited a lower compressive strength at early ages, which turned into a higher compressive strength beyond 7 days. The highest performances of concrete containing the PCCA compared to those made with conventional LWA might be explained by the finer pore system and the siliceous type of the PCCA.

Regardless of the curing efficiency, a continuous increase in compressive strength with both increasing curing time of concrete and the content of the PCCA can be observed. At 7 to 28 days, the improvement of the compressive strength reached the highest value and the gain in the compressive strength ranged between 13% and 51% compared to the gain obtained with the control concrete as shown in Fig. 3.

Although the NC mix has shown the highest compressive strength until 7 days, its 28-day compressive strength is the lowest one compared to the other HPC mixtures with and without internal curing. The moderate increase of the compressive strength of this mix is due to both the absence of additional water to supply the pozzolanic reaction between SF and portlandite, and the type of binder which is characterized by a high early compressive strength and an insignificant increase at later ages.

In fact, the benefits of the addition of the PCCA on the compressive strength development might be well illustrated by the relative strength which represents the relation of strength of a given mixture at a given age to the strength of reference mixture. Results presented in Fig. 4 indicate that the addition of the pre-saturated PCCA had a slight effect on early age strength (1 and 3 days); however, a substantial increase of the compressive strength at 28 days was achieved.

3.1.2. Splitting tensile strength (STS)

Although the compressive strength of HPC is the most important and largely studied, the tensile strength is critical for concrete subjected to tensile forces such as those induced by the development of autogenous shrinkage. This might allow the evaluation of the ability of a concrete mixture to resist the tensile stresses that are induced during the binder hydration reactions. The splitting tensile strength evolutions for the concrete mixtures studied are illustrated in Fig. 5 and the standard deviation for the three specimens tested were found to vary between 0.30 and 0.87 MPa. Generally, the inclusion of the PCCA has induced a slight decrease of the splitting tensile strength at both early and later ages and the increase of the content of the PCCA tends to decrease more the tensile strength of the internally cured concrete compared to the control mixture. This could be explained by a weak interfacial zone that is formed between the PCCA and the cement paste. The type of aggregate (ceramic) and the smooth surface of certain particles may have an effect on the bonding between the cement paste and aggregates. Simultaneous evolutions of both compressive and tensile strengths for the mixes investigated are presented in Fig. 6.

3.1.3. Young's modulus

While the Young's modulus of concrete is usually expressed as a function of compressive strength, it is mainly related to the coarse aggregate fraction and properties rather than the cement paste. A partial replacement of NCA by LWA might have a negative effect on the Young's modulus development [38,39]. Many authors [40,41] have pointed out the importance of the determination of the Young's modulus of HPC, however, to the best knowledge of the authors, rarely have studies about internal curing considered the effect of the addition of LWA on the Young's modulus development. Fig. 7 presents the results of Young's modulus evolution up to 28 days for both control and internally cured mixes. It shows that the tendency is quite similar to that observed with the splitting tensile strength development. Only a marginal decrease of the Young's modulus has been observed for the HPC mixtures containing the PCCA compared to the control mixture. Such a negative effect is mainly attributed to the type and mechanical characteristics of the substituted aggregate. In one hand, the crush rate results which could represent the resistance of an aggregate to sudden impact reveal that the NCA used are stiffer than the PCCA as indicated in Table 2. Therefore, coarse aggregate bulk of such different stiffness could have a significant effect on the Young's modulus of HPC. Aïtcin [19] and Baalbaki et al. [40] have demonstrated

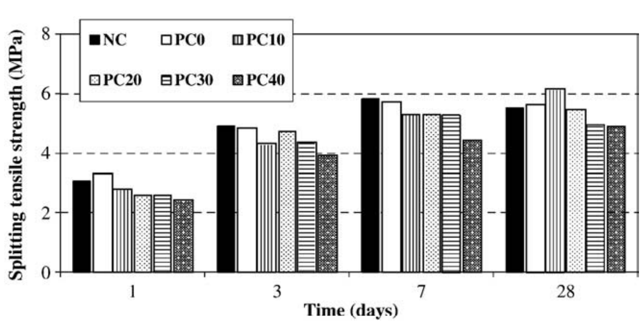

Fig. 5. Influence of the incorporation of the PCCA on splitting tensile strength development.

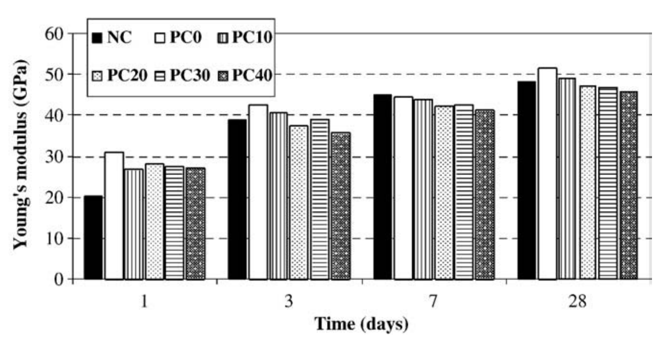

Fig. 7. Effect of the addition of the PCCA on Young's modulus evolution.

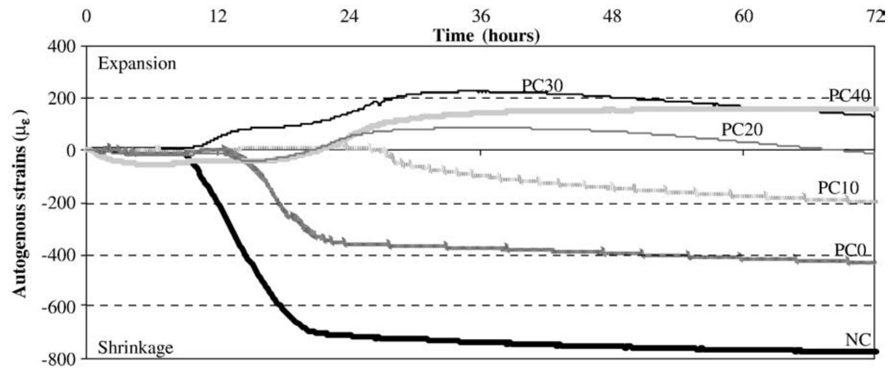

Fig. 8. Effect of the PCCA addition on early age autogenous strain development.

that the Young's modulus of concrete is influenced by the elastic properties and volume fraction of aggregates. Obviously, both the PCCA type and their pore network characteristics are different from that of the NCA which affect the elastic properties and consequently, the Young's modulus of mixtures containing the PCCA. On the other hand, while the Young's modulus is known to be strongly linked to the aggregate skeleton rather than to the cement paste still Young's modulus of concrete should be treated as a three-component composite: cement paste, aggregate skeleton and bond between them. It has been mentioned that interfacial transition zone (ITZ) has quite a significant effect on the overall Young's modulus of concrete and it is function of the surface area of aggregate, the fineness modulus as well as the aggregate gradation. As it can be concluded from Fig. 1 and Table 2, the PCCA have a higher surface area compared to the NCA which could increase the volume of the ITZ for mixtures internally cured with the PCCA and therefore affect their Young's modulus.

3.2. Autogenous shrinkage development

As the time zero is an important parameter that may overestimate/underestimate the ultimate magnitude of autogenous strains at a given age [42] and in order to point out the effect of the addition of the PCCA on the volumetric contractions at earliest age; it has been adopted to start measuring and recording the strains developed immediately after concrete placement in the moulds. The results obtained for autogenous shrinkage strains of the six HPC mixtures with and without the PCCA are plotted in Figs. 8 and 9. All concrete mixtures investigated have shown a relatively long dormant period which drastically turned into marked autogenous shrinkage strains for the two mixtures without the PCCA. However, HPC mixtures containing the PCCA at different proportions have shown a lengthened dormant period which turned into a significant expansion for the mixtures PC20, PC30 and PC40 as shown in Fig. 8. The shortest dormant period has been exhibited by the NC mixture followed by the PC0. The length of this dormant period during which no significant deformations have been recorded is mainly related to the mixture composition.

For the two control mixtures made without internal curing, the obtained autogenous shrinkage strain for the premixed low heat SF concrete (PC0) are much lower than those for the normal Portland cement with SF (NC). These two mixtures reach more than 90% of their 28-day ultimate magnitude of autogenous shrinkage during the first 72 h as shown in Fig. 8. It is believed that the binder type used (high belite cement) in the PC0 mix is responsible for the reduction of autogenous shrinkage as mentioned in previous studies [2–4,43,44]. The refinement process of the pore structure by the ultrafine SF particles along with the pozzolanic reaction with portlandite, leads to a considerable amount of autogenous shrinkage.

The internally cured HPC mixtures containing the pre-wetted PCCA are seen to provide a substantial reduction in the recorded autogenous strains up to 28 days. This reduction is intimately related to the content of the PCCA incorporated into the cement paste. The higher the content of the PCCA, the lower is the autogenous shrinkage exhibited. The largest reduction of autogenous shrinkage was reached using 40% of the pre-saturated PCCA as a partial replacement of the NCA. Adding 40% of the PCCA was able to completely eliminate the autogenous shrinkage up to 28 days and a non-shrinking HPC was thus obtained. While the internal curing of the mixtures with 30 and 20% has contributed to substantially reducing the autogenous shrinkage strains, still such amounts of the PCCA were not able to provide the internal water necessary for continuing hydration and then to completely eliminate the autogenous shrinkage. The lowest autogenous shrinkage reduction was provided by the PC10 mix for which a 35% reduction was achieved compared to the ultimate magnitude of the reference mixture.

Based on these observations, it seems that an amount of the PCCA ranging between 30–40% is the optimum level for internal curing which is sufficient to effectively mitigate both the early age and 28 day autogenous shrinkage strains of HPC as illustrated in Fig. 10.

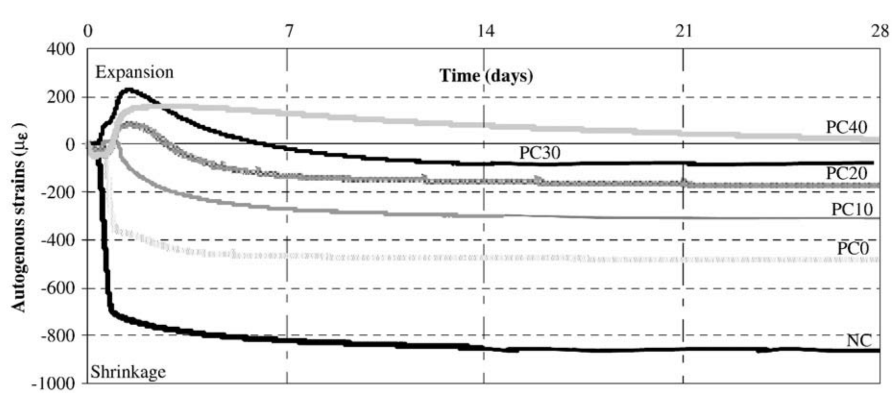

Fig. 9. Effect of the PCCA addition on autogenous strain development of concrete up to 28 days.

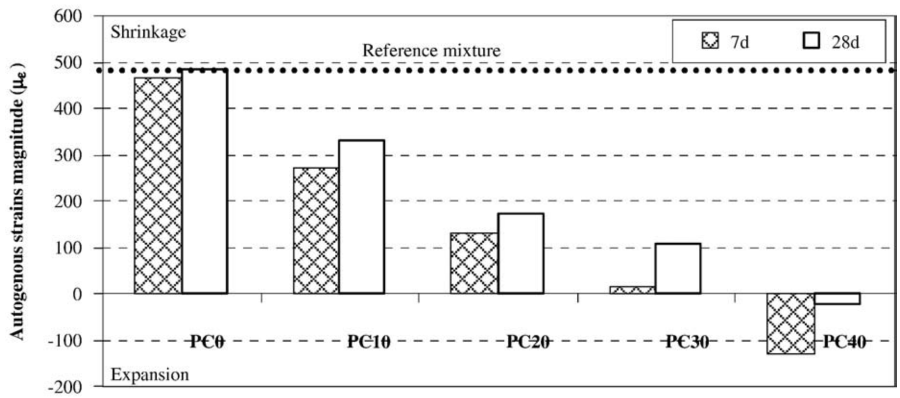

Fig. 10. The contribution of the PCCA in autogenous shrinkage reduction.

It is interesting to mention that the efficiency obtained by the incorporation of the PCCA particularly with an amount of 30% and 40% overcome largely that found in previous studies using conventional LWA in which the w/b of concrete was no less than 0.25. However, in the present study a much lower w/b of 0.15 has been used and the mixture PC40 with the waste recycled PCCA has completely eliminated the autogenous shrinkage up to 28 days. This indicates the high effectiveness of internal water curing provided by this new type of porous aggregate. Additionally, results have shown that HPC internally cured with 30% of the PCCA performs much better than concrete treated with combination of SRA and EXA [45].

3.3. Effect of the PCCA proportion on autogenous shrinkage

The effectiveness of internal curing provided by the waste ceramic aggregate depends mainly on the water transport characteristics within the cement matrix which are intimately related to the PCCA parameters including proportions, pore size and grain size distribution. As shown in Fig. 1, the grain size distribution of the PCCA ranged mainly between 5–15 mm with a small amount (3%) of grains having a size of 20 mm and 5% with size less than 5 mm. This could influence the distribution of the water reservoirs in the cement paste and therefore, the water transport may become limited to the distance surrounding the PCCA. Generally, the finer the grain size of aggregate, the shorter will be the distance from the location of the porous aggregate to the cement paste which might contain unhydrated cement particles. However, the pore size and absorption capacity of finer grains size is generally smaller than that of the coarser grains. The effect of the grain size distribution of the PCCA on the autogenous shrinkage development will be discussed in further work.

On the other hand, the effective optimum content of the PCCA for shrinkage reduction is strongly related to the w/b of the mixture. For the present mixture design with a w/b of 0.15, it seems that PCCA contents higher than 20% are very effective to considerably reduce the magnitude of autogenous shrinkage and even to completely eliminate it for 40% as shown in Fig. 10. Because the PCCA content which can effectively mitigate autogenous shrinkage for one w/b may be less effective for a lower w/b, the high efficiency obtained with the very low w/b used in the current study could be more effective for the higher w/b frequently used in construction field and laboratory testing which range usually between 0.40 and 0.25.

3.4. Effect of the PCCA addition on the induced stress

Internal capillary tensile stress is the result of self-desiccation of cement paste in the course of cement hydration. The ultimate magnitude and the evolution of internal tensile stress is strongly related to autogenous strains development.

Results for the induced stresses up to 28 days for the HPC mixtures investigated herein are presented in Figs. 11 and 12. It can be clearly observed that the internal capillary stresses are proportional to the autogenous strains development illustrated in Figs. 8 and 9. The higher the autogenous deformations are, the higher the capillary stresses that are induced. As shown in Fig. 11, the early age capillary stress development up to 3 days can be classified into two behavior modes: i) compressive stress for the mixtures containing a high proportion of the pre-saturated PCCA (PC20, PC30 and PC40), and ii) tensile stress for the control mixtures and the PC10 mixture with a low content of the PCCA. Their different behaviors might indicate clearly the contribution of the internal water curing provided by the PCCA in reducing the internal capillary stress. In fact, it is well known that hydration reaction

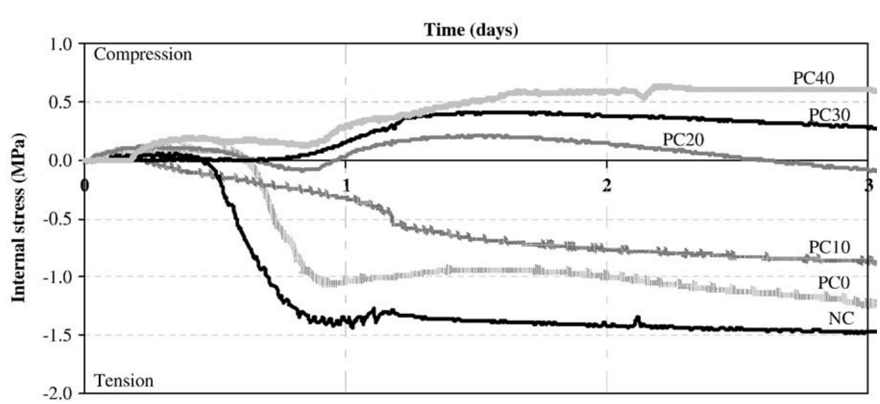

Fig. 11. Early age internal stress development of concrete mixtures with and without the PCCA.

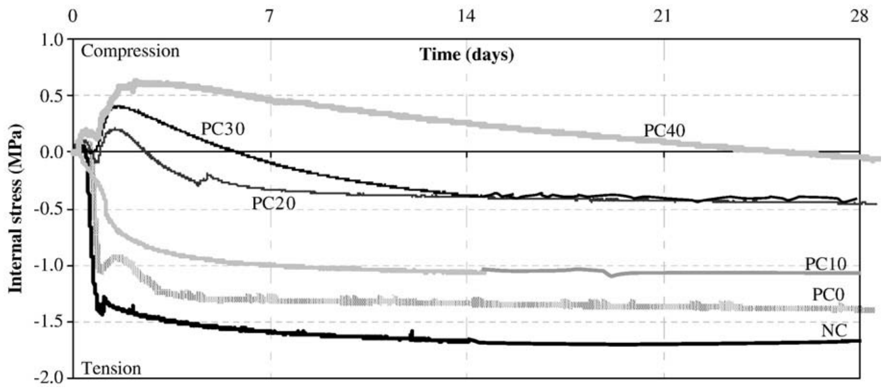

Fig. 12. Effect of the PCCA addition on internal capillary stress of concrete up to 28 days.

of cement results in the formation of both solid products and a capillary pore-filling network into the cement paste. As the cement hydration process progresses, the humidity in the cement paste decreases due to the consumption of capillary pore water which leads to the formation of meniscii in the capillaries. This process is recognized as the main mechanism that governs autogenous shrinkage development of the cement paste. As mentioned previously, in concrete mixtures that are internally cured, the pre-saturated PCCA acts as a water reservoir and the pore network of the cement paste absorbs the water that contained in this PCCA by capillary suction, maintaining water-filled capillary pores and avoiding the formation of meniscii and the development of internal capillary tension. Depending on the amount of water entrained by the PCCA added to the concrete mixtures and as long as it contributes to maintain the capillary pores in a saturated state, the capillary tension development could be mitigated as illustrated in Figs. 11 and 12. The higher the content of the PCCA and the water entrained, the lower will be the capillary tension.

Increasing the amount of the PCCA added to the concrete mixture leads to a drastic decrease of the induced capillary tension as indicated in Fig. 13 showing the contribution of the PCCA content in reducing the induced stress. Once the capillary pores become empty and the water contained in the PCCA is consumed or cannot reach the nearest pore due to the depercolation of the pore system, the meniscii form and the internal stress starts to develop and to increases over time.

Definitely, summarizing the effect of the addition of the waste porous ceramic coarse aggregate on autogenous shrinkage strains and stresses and mechanical behavior of HPC, it can be concluded that this new type of porous coarse aggregate when properly optimized and added in the amounts required can be used effectively as an internal water curing agent to significantly reduce or completely eliminate autogenous shrinkage and consequently, the induced capillary tension without any decrease of the compressive strength at either early or later ages.

4. Conclusions

The present study has focused on the use of by-product "porous ceramic waste aggregates" in HPC mixtures as a pre-saturated porous coarse aggregate in order to enhance the cement hydration reaction and reduce autogenous shrinkage. The results indicate that the waste recycled porous ceramic aggregate has a great potential for internal wet curing purposes and can be used successfully in HPC mixtures to significantly mitigate autogenous shrinkage.

The addition of different amounts of the pre-saturated PCCA in high-performance SF concrete to supply internal water curing has shown a high effectiveness to substantially reduce autogenous shrinkage and hence, mitigate the risk of early age cracking. An additional benefit of internal water curing provided by the use of the PCCA is an improvement of cement hydration reaction which results in a significant increase of the compressive strength beyond the autogenous shrinkage reduction effect. An enhancement of the 28-day compressive strength of about 10% to 20% for the concrete mixtures containing the PCCA was achieved.

Partial replacement of NCA by different contents of the PCCA resulted in a substantial reduction in both the ultimate magnitude and the development of autogenous shrinkage strains over time, and consequently, a reduction the internal capillary tensile stress. Increasing the amount of the PCCA leads to a significant decrease of the magnitude of autogenous shrinkage. It has been found that when the content of the PCCA changes from 10 to 40% by volume, the obtained magnitude of autogenous shrinkage reduces from 30% to 105%. A non-shrinking HPC (up to 28 days) was obtained using 40% of the PCCA, accompanied by a significant increase of the compressive strength for mixtures with a very low w/b of 0.15. The results have shown that reducing autogenous shrinkage by the incorporation of the PCCA leads to a significant decrease of the internal capillary tension in the cement paste. This decrease is proportional to the autogenous shrinkage decrease.

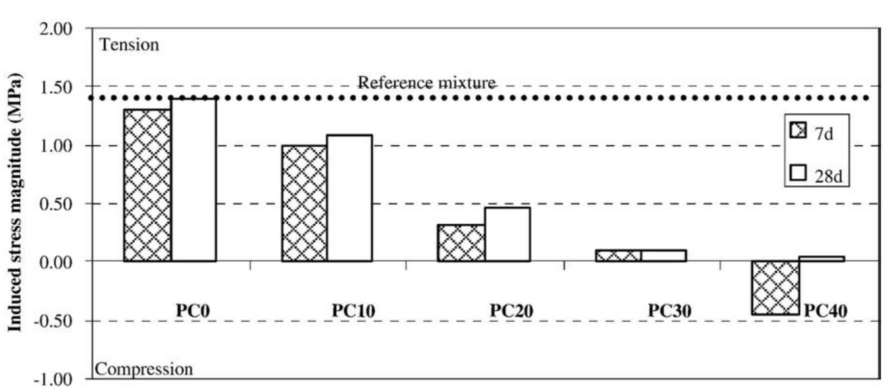

Fig. 13. The PCCA contribution to the capillary stress reduction.

Therefore, this new type of porous aggregate "PCCA" seems to be an attractive and reliable alternative compared to the conventional LWA both from the economical point of view and engineering properties. When properly applied and designed, HPC mixtures with the addition of the PCCA can be produced with low autogenous shrinkage and low internal tensile stress without any decrease of the compressive strength.

Therefore, internal water curing provided by the incorporation of the waste porous ceramic aggregate has revealed a high efficiency and promises to be a reliable technique to mitigate autogenous shrinkage and the induced capillary internal stresses.

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