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The mechanical, transport and thermal properties of mortar and concrete containing waste cork

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ABSTRACT

This study examines the impact of cork used as sand replacement or stone replacement on the plastic, mechanical, transport, microstructural and thermal properties of mortar and concrete. Mix design variables include the percentage of cork, cork size, and the cork blend. Key findings from this study revealed that: (i) The greatest early age (days 3 and 7) cube strengths were achieved by 24 h moisture saturation of the cork followed by draining it prior to use in concrete. Heat exposure of 50 °C or 100 °C resulted in detrimental effects on cube strength gain. (ii) Finer cork sizes were most beneficial to achieve optimum mechanical, and transport properties however high permeability values indicate that concrete-cork composites considered in this study may be vulnerable to poor durability performance. (iii) Greater percentages of cork as sand or stone replacement had the greatest impact on thermal resistance. (iv) Blending multiple cork sizes to achieve a greater size distribution of cork granules used as sand or stone replacement did not yield notable beneficial results.

1. Introduction

Cork is a renewable resource. It is a natural lightweight cellular material extracted from the bark of Cork Oak trees (Quercus suber) which are predominantly found in Portugal, Spain, and Algeria. To a lesser extent, Cork Oak trees are also grown in Morocco, Tunisia, Italy and France [1]. The world's cork production is estimated at 340,000 tons per year from approximately 22,000 km^2 of cork forest [1]. Currently, cork is used in many applications including bottle stoppers, flooring, noise barrier systems and aeronautical applications [2]. An estimated 75% of harvested cork is discarded as waste from the production of punched bottle stoppers. Some of this waste is ground into small granules of which the relatively larger granules are made into panel-like products for construction purposes. However, a large portion of the waste (20–25% by weight) remains under-utilized because the granules have a high density or are of very small dimensions or both [3]. It is estimated that annually, 68,000–85,000 tons of cork remains an under-utilized waste [3].

The primary chemical constituents of cork are, suberin (40%), lignin (20–22%), hemicellulose (11%), cellulose (9%) and extractives (15–20%) [3,4]. Due to its unique composition and cellular structure, cork exhibits low density, low thermal conductivity, good sound absorption and water resistance. Researchers have investigated the use or cork in composites such as cork/beverage carton wastes composite, hydroxypropylcellulose (a biocompatible polymer)–cork composites, and cork–charcoal board composite [2]. In the context of building materials, Hernandez-Olivares et al. [5] recognized the compatibility of cork and plaster and examined the feasibility of cork–gypsum composites. Their findings indicated that cork–gypsum composites have potential to be used as a partition walls owing to its thermal insulation properties and sound reflecting and absorption ability.

The initial motivation for including cork in concrete was to develop lightweight concrete [6]. More recently, literature reports have revealed a general consensus that incorporating cork in concrete improves its thermal resistance but reduces the mechanical properties [4,7,8]. The low density and high gas content of cork's cellular structure contributes to the low thermal conductivity. The mechanical properties of cement-cork blends are not only controlled by the cork's low density, but also the interaction of cork extractives with the cement hydration process. Karade et al. [3] reported that although the incorporation of cork granules greater than 2–3 mm reduce the compressive strength of cement–cork blends, they affect the cement hydration process less than relatively smaller granules (<0.2 mm).

Drawing on the desirable properties of cork, BenAbdallah et al. [9] studied the thermal and structural properties of cork fibre used to reinforce polypropylene plastics. Their findings indicated the importance of cork pretreatment, namely boiling in water for up to 3 h, on the structural and adhesion properties of plastic-cork blends. Castro et al. [10] studied the acoustic and thermal behavior

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of concrete blocks containing cork. Their results revealed that not only does the presence of cork improve the thermal behavior of concrete block walls, it also makes them lighter and easier to handle. Furthermore, their study emphasized the ecological benefits of using cork in concrete blocks. Based on the experiments reported by Castro et al. [10], the blocks containing cork were reported to reduce the thermal conductivity by 45% of blocks without cork and in addition reduced the CO_2 emissions associated with the block wall. Given that cork is a renewable resource, it has been reported to be a sustainable building material option. However, few studies have examined the microstructural development and its implications on the long term durability performance of concrete-cork products. Branco et al. [11] replaced entrained air with cork granules and evaluated the freeze–thaw durability effectiveness. They reported that cork can exhibit acceptable freeze–thaw resistance up to 28 freeze–thaw cycles, but beyond that severe and rapid deterioration occurs.

The motivation of this study is to investigate the viability and feasibility of combining waste cork with cementing materials in context with the plastic and hardened material properties. The objective of this study is to assess the implications of: preconditioning cork prior to its use in concrete; varying the percentages of cork as sand and/or stone replacement; use of only one cork size, and blends of different cork sizes on the composite materials plastic properties, evolution of mechanical properties, microstructure, and thermal resistance. This examination evaluates: (i) Cork properties and conditioning: The density of the cork was measured and the effect of various preconditioning regime consisting of heating and moisture saturation alone in combination were examined. (ii) Cork as sand replacement in mortar mixtures: The evolution of density, cube strength, and microstructure characterized using mercury intrusion porosimetry (MIP) of mortar mixtures at early ages, (day 7) and later ages (day 56) were assessed. (iii) Cork as sand and/or stone replacement in concrete mixtures: The slump, density, compressive strength, static elastic modulus, rapid chloride permeability (RCP) and thermal resistance were tested. Ten mortar mixtures, and nine concrete mixtures were examined.

2. Experimental program

2.1. Materials and mix design

The materials used in this study were General Use (GU) cement, granulated waste cork, natural sand and crushed limestone. The chemical composition of the GU cement is presented in Table 1. The natural sand has a specific gravity, fineness modulus and absorption of 2.72, 2.84, and 1.5%, respectively. The crushed limestone has a nominal maximum size of 13 mm and a specific gravity of 2.70.

Table 1
Chemical composition of cementing material.

Constituent	GU cement (% by mass)
SiO_2	19.24
$A1_2O_3$	5.43
Fe_2O_3	2.36
CaO	60.94
MgO	2.34
SO_3	4.11
K_2O	1.11
Na_2O	0.22
TiO_2	0.26
SiO	0.08
P2O5	0.12
Cl	0.03
ZnO	0.02
Cr_2O_3	0.01
Mn_2O_3	0.06
Leco CO_2	2.22
Leco SO_3	3.95
Free lime	1.10

The mortar and concrete mix proportions, namely the cork size, percentage of cork as sand and/or stone replacement are summarized in Table 2. Five cork particle size categories were used and consist of (0.5–1), (2–3), (3–5), (3–8) and (6–14) mm. All mortar mixtures were prepared as 1:2 mortars (i.e. 1 part cement to 2 parts sand by mass) with a water-to-binder (w/b) ratio of 0.40. All mortar mixing was conducted in accordance with ASTM C305 [12]. The mortar mix design variables examined included the percentage of cork as sand replacement (0%, 10% and 20%). Some experiments were conducted with a single cork size range (0.5–1, or 2–3 or 3–5 mm), while other mortar mixes included blends which were 50:50 combinations (by mass) of two of the previously mentioned sizes.

All concrete mixtures were prepared in accordance with CSA A23.2-2C [13]. The concrete mixtures were designed based on a cement content of 400 kg/m^3, w/b ratio of 0.40 and a coarse aggregate content of 35% by volume. Both a water reducing (WR) agent and a superplasticizer (SP) were used for the concrete mix designs. For each concrete mixture, the slump was evaluated in accordance with CSA A23.2-5C [13]. The concrete mix design variables examined were cork size, cork gradation, type of aggregate replaced (sand, stone or both), and the percentage of aggregate replaced (0–20%), as reported in Table 2. The cork gradations used, namely 'cork as sand blend', and 'cork as stone blend' are respectively defined as:

Cork as Sand Blend = 3.7%(3–5 mm) + 29.6%(2–3 mm) + 58.2%(0.5–1 mm) + 8.6%(<0.2 mm).

Cork as Stone Blend = 33.7%(6–14 mm) + 62.4%(3–8 mm) + 3.9%(2–3 mm).

The 'cork as sand blend' and 'cork as stone blend', were proportioned to have the same gradation (by mass) of the sand and crushed stone. Nine concrete mixtures were prepared according to Table 3, which were based on the measured cork densities reported in Table 4. All mortar and concrete specimens were demoulded 24 h after casting. The mortar specimens were cured at temperature of 23 ± 2 °C in saturated limewater until tested. The concrete specimens were cured in a moist room at 100% relative humidity and a temperature of 23 ± 2 °C until tested.

2.2. Cork conditioning

The relatively high hemicellulose content in wood has been shown to retard cement hydration processes. Although, Karade et al. [3] reported that the hemicellulose content in cork is relatively lower, tannins in cork may impact the hydration mechanism of cement if released from the cork. Tannis are located in the central vacuoles of cork cells and provide some protection to the bark, for example by protecting it from insects and animals feeding on it.

In order to assess the impact of tannins present in waste cork on the development of cement–cork properties, four combinations of heat exposure and moisture saturation of the cork were examined on mortar mixture M4. Regime 1 consisted of soaking the cork granules in water for 24 h. A 4 L beaker was filled with cork and water. To keep the cork submerged, a weighted lid was placed on the beaker before it was filled with water as illustrated in Fig. 1a. After soaking, the cork was drained for a minimum of 24 h by placing it in a plastic bag with its bottom replaced by a perforated surface, shown in Fig. 1b. The smallest cork size (less than 1 mm) was difficult to handle owing to its lightweight and fineness. Furthermore,

Table 2
Use of cork in mortar and concrete mix designs.

Material	Mix	Identification	Cork Size (mm)	Percentage replacement (%)	Sand or stone replacement
Mortar	M1	Control	None	0	
Mortar	M2	10%C(0.5–l)	(0.5–1)	10	Sand
Mortar	M3	10%C(2–3)	(2–3)	10	Sand
Mortar	M4	10%C(3–5)	(3–5)	10	Sand
Mortar	M5	5%C(0.5–l) + 5%C(2–3)	(0.5–1) + (2–3)	5 + 5	Sand
Mortar	M6	5%C(0.5–l) + 5%C(3–5)	(0.5–1) + (3–5)	5 + 5	Sand
Mortar	M7	5%C(2–3) + 5%C(3–5)	(2–3) + (3–5)	5 + 5	Sand
Mortar	M8	20%C(0.5–l)	(0.5–1)	20	Sand
Mortar	M9	10%C(0.5–l) + 10%C(2–3)	(0.5–1) + (2–3)	10 + 10	Sand
Mortar	M10	10%C(0.5–l) + 10%C(3–5)	(0.5–1) + (3–5)	10 + 10	Sand
Concrete	C1	Control	None	0	
Concrete	C2	10%C(0.5–l)	(0.5–1)	10	Sand
Concrete	C3	10%C(3–5)	(3–5)	10	Sand
Concrete	C4	10%CSandBlend	Cork as sand blend[a]	10	Sand
Concrete	C5	10%C(3–8)	(3–8)	10	Stone
Concrete	C6	10%C(6–14)	(6–14)	10	Stone
Concrete	C7	10%CStoneBlend	Cork as stone blend[b]	10	Stone
Concrete	C8	5%CSandBlend + 5%CStoneBlend	Cork as sand and stone blend	5 + 5	Sand and stone
Concrete	C9	10%CSandBlend + 10%CStoneBlend	Cork as sand and stone blend	10 + 10	Sand and stone

[a] Cork as sand blend = 3.7%(3–5 mm) + 29.6%(2–3 mm) + 58.2%(0.5-lmm) + 8.6%(<0.2 mm).
[b] Cork as stone blend = 33.7%(6–14 mm) + 62.4%(3–8)mm + 3.9%(2–3 mm).

Table 3
Concrete mix design.

Mix	Identification	GU cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Stone (kg/m^3)	Cork as sand (kg/m^3)	Cork as stone (kg/m^3)	WR[a] (mL/m^3)	SP[b] (mL/m^3)
C1	Control	400	160	930	945	0	0	1400	2000
C2	10%C(0.5–l)	400	160	603	945	67	0	1400	2000
C3	10%C(3–5)	400	160	563	945	62	0	1400	2000
C4	10%CSandBlend	400	160	639	945	71	0	1400	2000
C5	10%C(3–8)	400	160	930	518	0	57	1400	2000
C6	10%C(6–14)	400	160	930	495	0	55	1400	2000
C7	10%CStoneBlend	400	160	930	504	0	56	1400	2000
C8	5%CSandBlend + 5%CStoneBlend	400	160	770	665	40	35	1400	2000
C9	10%CSandBlend + 10%CStoneBlend	400	160	639	504	71	56	1400	2000

[a] WR = water reducer.
[b] SP = superplasticizer.

Table 4
Density of cork.

Cork size (mm)	Density (kg/m)
(0.5–1)	550
(2–3)	490
(3–5)	460
Cork as sand blend	670
(3–8)	360
(6–14)	330
Cork as stone blend	340

draining the fine particles was not very effective because of the large surface area and the surface tension of water. To extract this water and also the tannins, the cork was placed between two pieces of filter paper in a hydraulic press. Pressure up to 1000 kPa was gradually applied while the water was allowed to drain. The cork was then conditioned to a saturated surface dry state.

Conditioning Regime 2 consisted of heating the cork granules at 50 °C for 24 h; soaking the cork for 24 h in water; then draining and pressing the cork to remove the water and conditioning to saturated surface dry state. Regime 3 was the same as Regime 2 except the heating temperature was 100 °C. Regime 4 simply was to use the cork as it was received which was dry, with no heat exposure. It should however be noted that the cork ‘as received’ is waste cork from cork stoppers, and during the manufacturing process the cork stoppers, it was initially exposed to boiling water, intended to remove microflora and/or microorganisms [14].

2.3. Plastic and hardened density

The fresh density of the mortar was measured using an adaptation of the procedure in CSA A23.2-6C [13]. For this measurement, a 1.2 L container was filled in three layers of equal volume. Each layer was rodded 20 times with a 10 mm diameter rod with a hemispherical end. For the concrete, CSA A23.2-6C [13] was followed. A 7 L container was filled in three layers and each layer was rodded 25 times with a 16 mm diameter rod with a hemispherical end.

The hardened density (ρ, kg/m^3) of the mortar and concrete was calculated based on the mass of the mortar cube or concrete cylinder in air (M_a) and the apparent mass of the cube or cylinder in room-temperature water (M_w) using

$$\rho = 997.5\frac{M_a}{M_a - M_w} \qquad (1)$$

2.4. Mechanical properties

The cube strength of the mortar samples was measured in accordance with ASTM C109-08 [15]. At each age (7, 14, 28 and 56 days), three 50 × 50 × 50 mm cubes per mix were tested. The concrete compressive strength was measured in accordance with ASTM C39-05 [16]. Three 100 × 200 mm cylinders were tested at each age (7 and 28 days). The static elastic modulus of the concrete

Fig. 1. (a) Soaking and (b) draining the cork granules.

samples was measured in accordance with ASTM C469-02 [17]. Two cylinders were tested at each of 7 and 28 days.

2.5. Microstructural characteristics

2.5.1. Mercury intrusion porosimetry

Mercury intrusion porosimetry (MIP) was conducted on mortar samples using a Quantachrome Autoscan porosimeter to a maximum pressure of 414 MPa. The test was conducted in accordance with ASTM D4404-84 [18]. A sample weighing approximately 2 g was chiselled out of the edge surface of the mortar cube. Prior to testing, the samples were placed in a desiccator under vacuum for 2 weeks to remove free water from the pores and also to minimize carbonation of the samples. The MIP test was conducted to determine the pore size distribution, and total porosity.

2.5.2. Rapid chloride permeability

Rapid chloride permeability (RCP) was conducted on the concrete specimens to evaluate the relative permeability of concrete to chloride ion migration. The procedure employed was ASTM C1202 [19]. The test specimens (50 mm puck cut from a standard 100 × 200 mm cylinder) were first vacuum-saturated for 24 h and then placed in the apparatus, where each side of the test cell was filled with an electrolyte (0.3 M NaOH, 3% NaCl). A charge of 60 VDC was passed across the sample for six hours and the total current passed was measured. For each mix design, two cylinders were tested yielding two measurements representing the pucks retrieved from the top of the cylinders and two measurements on the pucks from the bottom of the cylinders.

2.6. Thermal resistance

Thermal resistance of the concrete was evaluated based on the apparatus and procedure similar to that described in ASTM C177-10 [20]. A guarded hot plate apparatus was fabricated to be used to evaluate the thermal resistance of the concrete cork composite as shown in Fig. 2a. The apparatus also requires louvers, as shown in Fig. 2b, to shield the specimen from direct heat. The test was conducted by placing a 303 × 303 × 69 mm concrete slab with attached thermocouples in the apparatus' opening. After sealing the edges with tape to prevent air leakage, the entire assembly was placed in a refrigerator for 24 h minimum, as shown in Fig. 2c. The test was run for 14 h, starting when thermal equilibrium was reached. Duplicate temperature measurements were taken every 30 s on the inside and outside surfaces of the concrete and in the foam box.

Heat flow through an object follows the model in Equation (2), where Q is the total heat flow (J), q is the heat flux (W), A is the area perpendicular to the heat flow (m^2), R is the thermal resistance of the section (m^2 K/W), Δt is the temperature drop across the object (K) and T is the elapsed time (sec). If the test is run with a constant energy input, then the second form of Eq. (2) can be used.

$$Q = \frac{A}{R}\Delta tT \qquad or \qquad q = \frac{A}{R}\Delta t \tag{2}$$

In the apparatus used, the energy input from the light bulb was distributed among the six sides of the box such that $q = q_1 + q_2 + q_3 + q_4 + q_5 + q_6$. Substituting Eq. (2) and rearranging, reduces to Eq. (3), where the subscripts c and E refer to the concrete and expanded polystyrene box, respectively.

$$R_c = A_c\Delta t_c\left(q - \frac{A_E}{R_E}\Delta t_E\right)^{-1} \tag{3}$$

3. Results and discussion

3.1. Cork density and cork conditioning

Table 4 presents the measured cork densities. The density increases as the cork size decreases. To examine the effect of the preconditioning treatment applied to the cork, on the early age evolution of cube strength, four different conditioning regimes were examined. The cork conditioning regimes consisted of different levels of soaking and heating the cork, prior to blending it with cement as detailed in Section 2.2. Table 5 summarizes the four conditioning regimes and the measured 3 day and 7 day cube strength. The effect of the 50 °C and 100 °C heat exposure of the cork proved to have a negative effect on the strength gain when combined with cement. In contrast, moisture saturation of cork followed by draining and conditioning to saturated surface dry state had a beneficial effect on the development of cube strength of cement–cork mortars. The beneficial effect of the moisture saturation followed by drying is expected to be attributed to the release of tannins which, if present, can inhibit the hydration process. A notable observation was that after moisture saturation, the drained solution was a dark brown color which was evidence that tannins and extractives had leached out of the waste cork. This observation is was also reported by BenAbdallah et al. [9] who showed that boiling cork in water for up to 3 h released impurities and extractive compounds from the cork.

The results shown in Table 5 reveal that at 3 and 7 days, the mortar exposed to Regime 1 and 2 were approximately 50% stron-

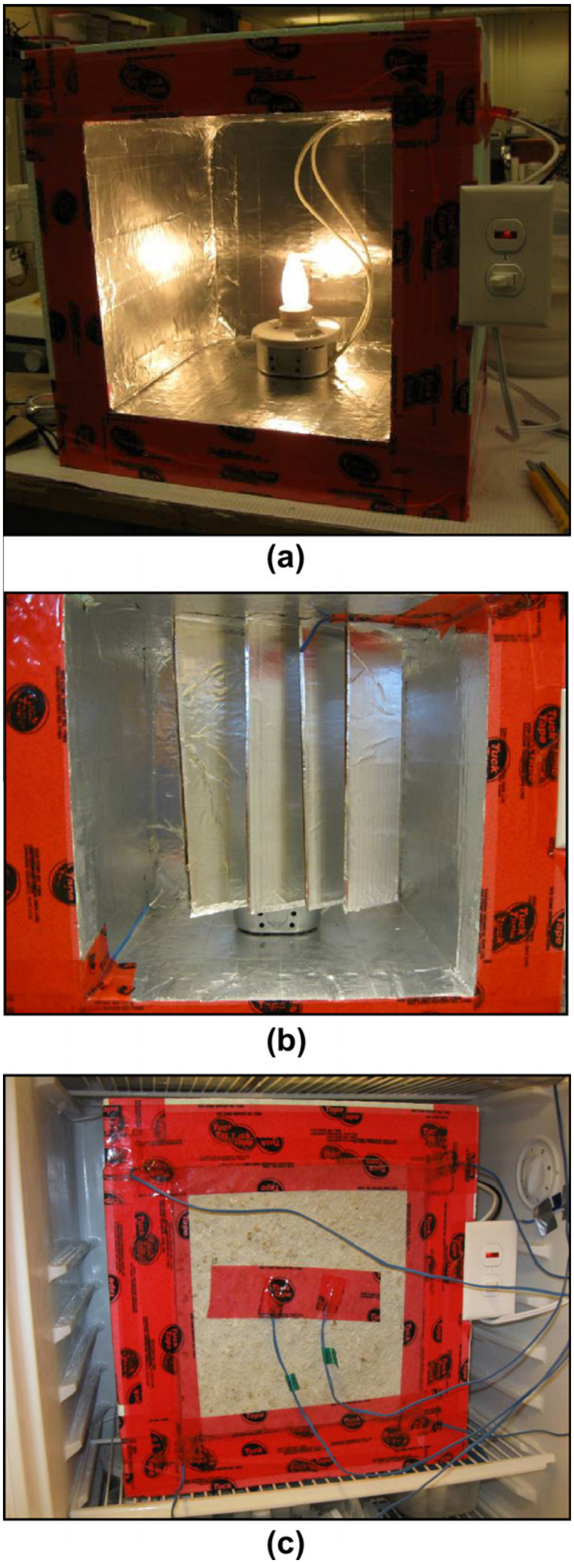

Fig. 2. Thermal resistance test set up (a) guarded hot plate apparatus (b) apparatus with louvers to shield concrete, and (c) installation of concrete slab and thermocouples ready for testing.

ger than those specimens containing cork conditioned in accordance with Regime 4, while Regime 3 resulted in marginally weaker specimens than those subjected to Regime 1 and 2. Based on these results, all mortar and concrete mix designs for the remainder of this investigation were prepared in accordance with Regime 1, namely, the cork was soaked, drained, and prepared to a saturated surface dry condition without any heat treatment.

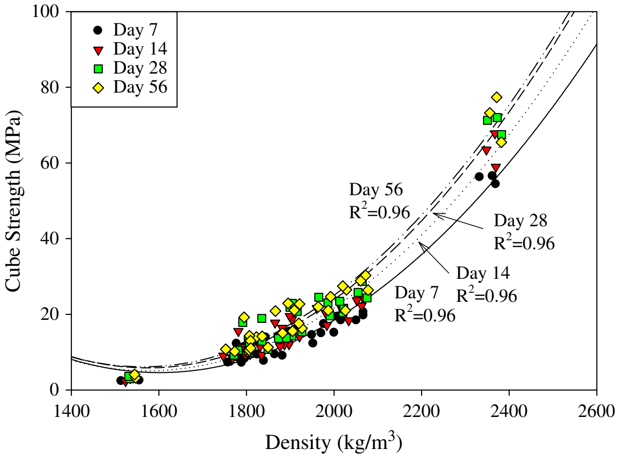

Fig. 3. Correlation between hardened density and cube strength.

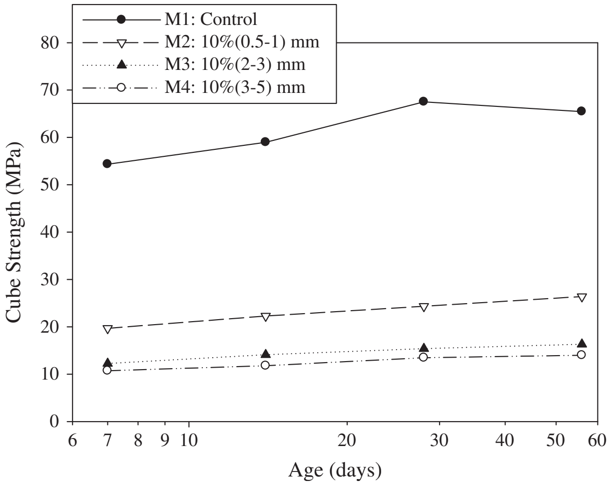

Fig. 4. Effect of cork size on cube strength.

3.2. Properties of cement–cork mortar

3.2.1. Workability

The workability of the fresh mortar decreased as the cork size and content increased. No water reducing admixtures were used in the mortar mixtures. Many of the mixtures containing 20% cork were unworkable, particularly those containing large cork granules. Consequently, the 20% cork blends, as indicated in Table 2 as mix M8, M9 and M10, consist of the smallest cork size (0.5–1 mm) exclusively or in combination with another size.

3.2.2. Hardened density and cube strength

The hardened density of the mortar mixtures were measured at ages of 7, 14, 28 and 56 days and are summarized in Table 6. All mortar density measurements are an average of three with a coefficient of variations (COVs) of 2% at most. The density of the mortar mixtures remained relatively constant over time. The density of the control specimen was 2369–2382 kg/m^3 and decreased with increasing percentage of cork.

The mean cube strength of the mortar mixtures and their corresponding COVs were measured at ages of 7, 14, 28 and 56 days and

Table 5
Effect of cork conditioning regime on cube strength.

	Conditioning procedure	Cube strength (MPa)	
		3 days	7 days
Regime 1	Soaked 24 h then drained	9.0	11.8
Regime 2	Heated for 24 h at 50C then soaked for 24 h then drained	9.2	11.0
Regime 3	Heated for 24 h at 100C then soaked for 24 h then drained	8.5	9.6
Regime 4	As received	6.2	7.2

Table 6
Mortar density (kg/m^3).

Mix	Identification	7 days	14 days	28 days	56 days
M1	Control	2370	2369	2382	2382
M2	10%C(0.5–l)	2067	2063	2075	2078
M3	10%C(2–3)	1953	1921	1927	1927
M4	10%C(3–5)	1806	1809	1815	1823
M5	5%C(0.5-l) + 5%C(2–3)	2001	2033	2020	2026
M6	5%C(0.5-l) + 5%C(3–5)	1971	1984	1991	1987
M7	5%C(2–3) + 5%C(3–5)	1898	1897	1904	1919
M8	20%C(0.5–l)	1840	1835	1849	1849
M9	10%C(0.5–l) + 10%C(2–3)	1796	1798	1807	1806
M10	10%C(0.5–l) + 10%C(3–5)	1764	1768	1772	1773

are summarized in Table 7. As mentioned, the density of the mortar mixtures remains constant over time however, the cube strength increases with age. A quadratic relationship exists between the density of the mortar and its cube strength as shown in Fig. 3.

Further examination reveals that the cube strength of the control mixtures (0% cork) increases from 54.3 MPa to 65.5 MPa from days 7 to 56, respectively. For the control specimen (M1), although there is a small decrease in mean cube strength from 67.5 MPa at day 28 to 65.5 MPa at day 56 this can be explained by the relatively high COV, 15%, at day 56. The mortar containing cork as sand replacement had a markedly lower cube strength in comparison to the control mixture. For mixtures containing 10% cork, the 7 day cube strength ranged from 10.7 to 19.7 MPa and increased to 14–26.4 MPa by day 56 depending on the cork size or combination of cork sizes used. The results reveal that for 10% cork as sand replacement, the mixture to achieve the highest cube strength at all ages, was mix M2 which incorporated the finest cork size, 0.5–1 mm. When the cork size increased from (0.5–1 mm) to (2–3 mm) to (3–5 mm) the mortar cube strength decreased as shown in Fig. 4. This is expected to be due to the lower cork density of the larger cork granules.

The effect of blending the two cork sizes on the cube strength gain is shown in Fig. 5. Statistical analysis of the results plotted in Fig. 5a indicates that the 50:50 blend of the (0.5–1 mm) and (2–3 mm) cork used as 10% replacement denoted as mix M5, has a statistically significantly lower cube strength than M2 which consists of 10% (0.5–1 mm) cork alone, but statistically significantly greater than M3 which consists of 10% (2–3 mm) cork. Statistical significance testing was based on the student's *t*-test to a 95% confidence level. Statistical analysis of the results reported in Fig. 5b indicates that the 50:50 blend, M6, exhibits a statistically significantly lower cube strength than M2 (0.5–1 mm), but greater than M4 (3–5 mm). In both comparisons, Fig. 5a and b, the blended mixtures, M5 and M6 have cube strengths that are approximately the average of the mortars consisting of each constituent alone.

Fig. 5c prsents the strength evolution of mixtures M3 consisting of 10% (2–3 mm) cork, M4 consisting of 10% (3–5 mm) cork, and a 50:50 blend of (2–3 mm) and (3–5 mm) cork, M7. At days 28 and 56, the difference between the mean cube strengths of mixtures M3 and M7 is not statistically significant at 95% confidence level nor for mixtures M4 and M7. The results in Fig. 5c suggest that for relatively coarser cork (>2 mm), cork size and cork gradation have little impact on the cube strength, in comparison to Figs. 5a and b which contain mixtures with finer cork. For example, the difference in cube strength between the M3 (2–3 mm) and M4 (3–5 mm) mixtures is 14–19% depending on the age. However, comparing mortar mixtures M3 and M4 to M2 which contains the finest cork size, the differences in cube strength are much larger. The strength difference between M2 (0.5–1 mm) and M3 (2–3 mm) ranges from 57–62%, and between M2 (0.5–1 mm) and M4 (3–5 mm) is 80–89% depending on the age.

Mixtures with 20% cork as sand replacement, the range of cube strength was much narrower, 7.4–8.2 MPa at day 7 and increased only slightly to 10.2–11.3 MPa after 56 days. Recognizing that the cement content for mixtures with 10% and 20% cork is the same, mortars with 20% cork had a significant effect on reducing the rate of hydration. Furthermore, the cork size and cork gradation had less of an effect on the cube strength in comparison to the percentage of cork. There was no statistically significant difference between the mean measured cube strengths for the blended mortars containing 20% cork, namely M9 and M10, in comparison to mortar M8 consisting of only 0.5–1 mm cork. The student's *t*-test was conducted to a 95% confidence interval based on the means and COVs reported in Table 7.

Table 7
Mortar cube strength (MPa).

Mix	Identification	7 days		14 days		28 days		56 days	
		Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
M1	Control	54.3	8	59.0	8	67.5	2	65.5	15
M2	10%C(0.5–l)	19.7	3	22.3	3	24.3	4	26.4	3
M3	10%C(2–3)	12.2	3	14.1	5	15.4	2	16.3	6
M4	10%C(3–5)	10.7	4	11.8	8	13.5	4	14.0	7
M5	5%C(0.5–l) + 5%C(2–3)	15.1	14	18.4	12	20.5	7	21.0	15
M6	5%C(0.5–l) + 5%C(3–5)	15.0	13	17.1	14	19.6	4	21.0	10
M7	5%C(2–3) + 5%C(3–5)	12.3	2	12.1	15	14.3	10	17.6	17
M8	20%C(0.5–l)	7.7	6	9.3	8	10.7	3	11.3	9
M9	10%C(0.5–l) + 10%C(2–3)	8.2	5	9.3	0	10.0	6	10.5	4
M10	10%C(0.5–l) + 10%C(3–5)	7.4	11	8.5	9	9.2	11	10.2	12

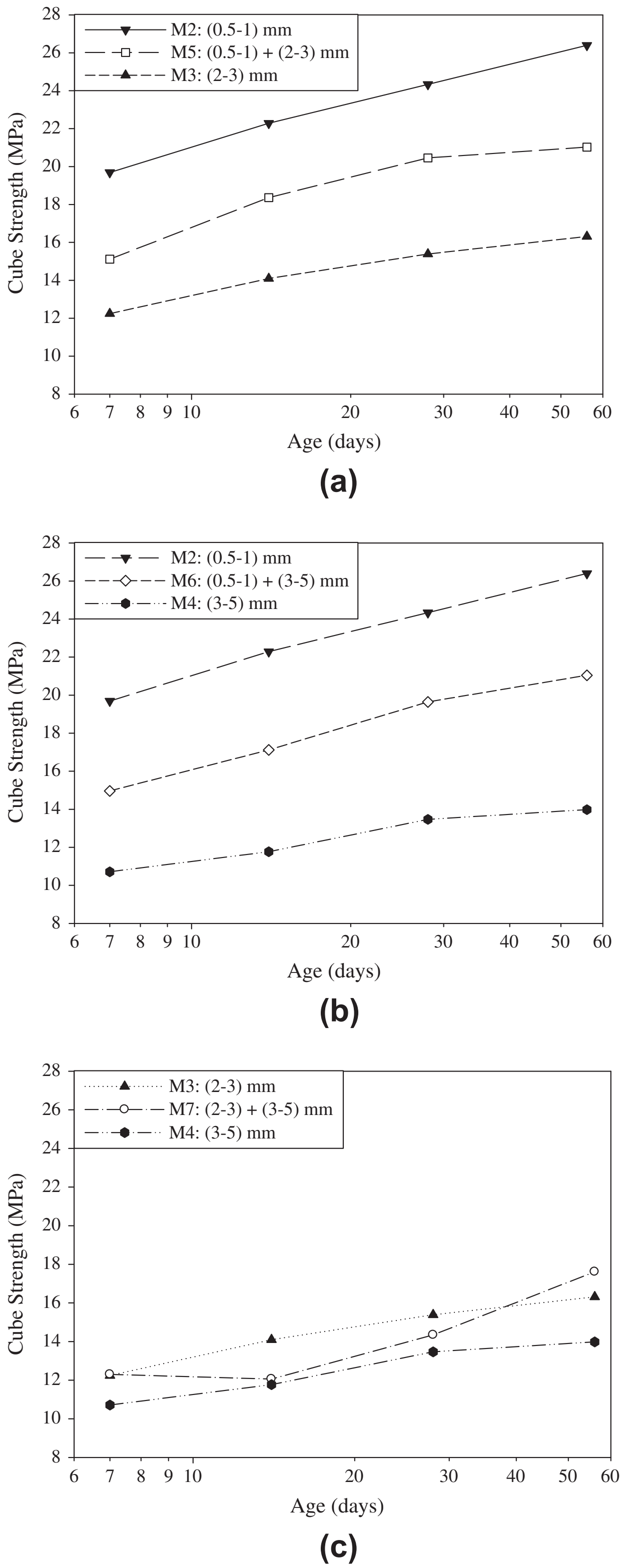

Fig. 5. Cube strength influenced by cork gradation (a) mixture M5, (b) mixture M6, and (c) mixture M7.

3.2.3. Influence of cork gradation on microstructure

At an age of 28 days, the microstructure of the control mixture, M1, and six mortar mixtures (M2-M7) containing 10% cork were examined using MIP to assess the impact of cork size on the pore size distribution and the total porosity. Increasing cork size as sand replacement yields a coarser pore structure as shown by the pore size distributions plotted in Fig. 6. The total porosity of the control mixture is 4.9% and for a 10% cork replacement, the porosity increases with increasing cork sizes.

In addition to cork size, the effect of cork gradation on porosity was also examined. Fig. 7 shows that when two cork sizes are combined 50:50 by mass, the total porosity of the mortar is greater than the porosity of mortar consisting of only one size of cork. However, further examination of the pore size distributions reveal that although the blended mortars, M5, M6, and M7 as shown in Figs. 7a, 7b, and 7c, respectively, have larger total porosity, compared to that of its constituents there are differences in the pore size distribution. Fig. 7a and 7b shows that in comparison to M3, and M4, respectively, the mortars containing (0.5–1 mm) cork as a constituent in its cork blend, has a lower or equal volume of pores that are 0.70–0.014 μm and a higher volume of fine pores which range from 0.01–0.0035 μm. In contrast, Fig. 7c, shows that the 50:50 blended cork, M7, has a coarser pore size distribution and has a larger pore volume of all sizes in comparison to the M3 and M4 mixtures.

3.3. Properties of concrete containing cork

3.3.1. Workability

The concrete slump test results are presented in Fig. 8. The influence of 10% and 20% cork in the concrete markedly decreased the slump measurements resulting is a less workable mixture compared to the control concrete, C1. However, no observed correlation was identified between the cork size, or percentage of cork used and the slump. The control concrete (C1) had a slump of 155 mm, concrete containing cork as sand replacement (C2, C3, C4) had slumps ranging from 5 to 25 mm, concrete containing cork as stone replacement (C5, C6, C7) had slumps from 10 to 40 mm and concrete containing cork as sand and stone replacement (C8, C9) had slumps of 10–15 mm. It should be noted that the slump was so low for three mixtures, C2, C8 and C9, that the mixtures were retempered with superplasticizer. This is reflected in the values reported in Fig. 8.

3.3.2. Concrete plastic density

Fig. 9 illustrates the concrete plastic density as indicated by points and the corresponding cork density which is indicated by bars for mixtures C1–C9. As shown by mixtures C2–C4, the concrete density is proportional to the cork density. For example, the density of the (0.5–1 mm) cork, 550 kg/m^3, used in concrete mix C2 is greater than the 460 kg/m^3 density of the (3–5 mm) cork,

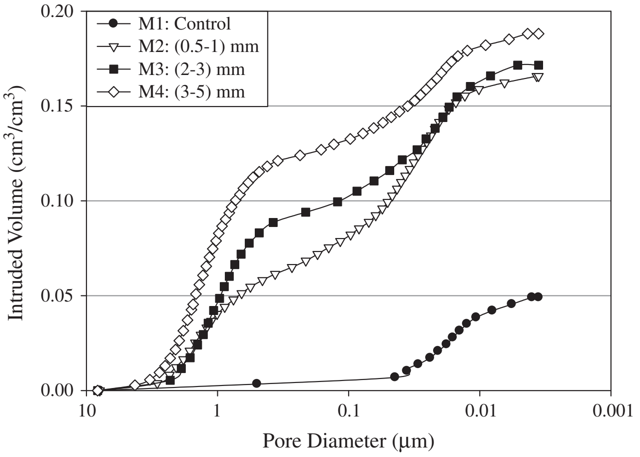

Fig. 6. Effect of cork size on pore size distribution.

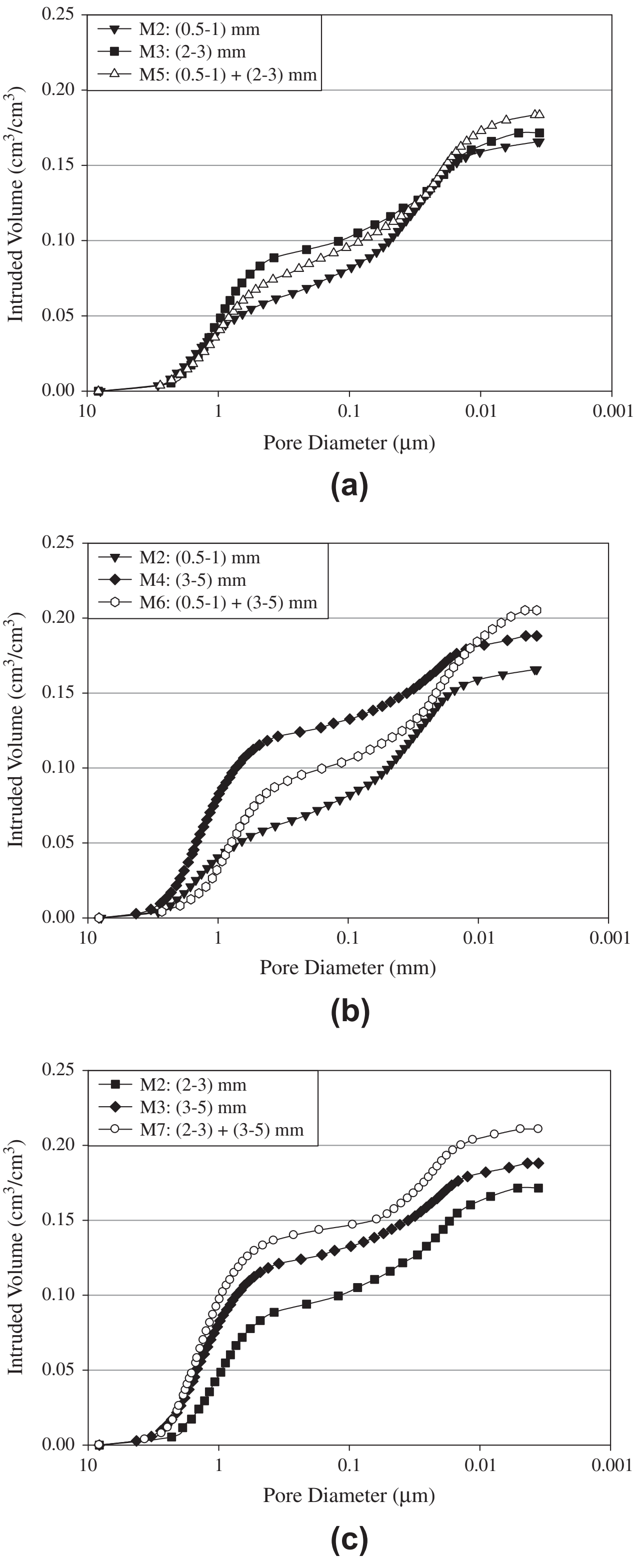

Fig. 7. Pore size distribution influenced by cork size and gradation (a) mixture M5, (b) mixture M6, and (c) mixture M7.

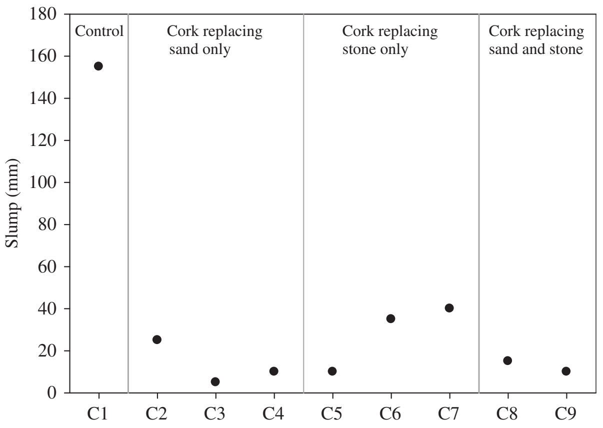

Fig. 8. Influence of cork on slump test results.

used in mix C3 and is reflected by the lower concrete density of the latter. Concrete mixture C4 has the highest plastic density which is consistent with the high density of the cork blend to replace sand, 670 kg/m^3. Concrete containing cork as sand replacement has plastic densities greater than concrete containing cork as stone replacement. Irrespective of the cork size used as 10% stone replacement, the concrete plastic density and the cork density are similar for all three mix designs, C5, C6, and C7 as shown in Fig. 9. The effect of increasing the percentage of cork used as sand and stone replacement from 10% to 20%, yields a 15% drop in concrete plastic density based on C8 and C9 mixture measurements.

3.3.3. Mechanical properties

The mean hardened density, compressive strength and the static elastic modulus of the concrete mixtures measured at 7 and 28 days are summarized in Table 8. In general, similar densities were measured between days 7 and 28 for the same mix design and all had a COV less than 2%. The 28 day density of the control concrete was 2456 kg/m^3. Mixtures containing 10% replacement of sand or stone, had similar densities, and the concrete density of the mixture with 20% cork was further reduced.

Fig. 10 shows the compressive strength ± one standard deviation for each concrete mix at days 7 and 28. In comparison to the control concrete, C1, mixtures containing 10% cork as sand and/or stone replacement have a 51–66% lower mean compressive strength based on the 7 and 28 days data. The concrete containing 10% cork, all continued to gain 14–17% compressive strength from days 7 to 28 indicating a lower rate of hydration in comparison to the 25% compressive strength gain from days 7 to 28 of the control concrete, C1. Even with the same cementing material content used in all mixtures, the results revealed that the presence of cork influences hydration reactions. This indicates that although the cork conditioning Regime 1 that was discussed in Section 3.1, had the least inhibiting effect on hydration reactions, waste cork has a significant effect on the development of the matrix structure and hydration. This was further supported by the compressive strength results for the mixture that contained 20% cork, C9. Mixture C9, did not gain compressive strength with age, and exhibited an 83% and 86% lower compressive strength at days 7 and 28, respectively, in comparison to the control concrete, C1. Beyond the reduction in mean compressive strength for mixtures containing 20% cork, the rate of hydration was also affected. Compared to concrete C1 and C4 which both experienced a 25% strength increase from days 7 to 28, the rate of strength gain was drastically reduced for mix, C9. Based on the mean values, although a 7% increase in compressive strength from days 7 to 28 was calculated, the strength gain from days 7 to 28 is statistically insignificant based on the student's *t*-test at a 95% confidence level.

Comparing mixture C2–C3 in Fig. 10 reveals that increasing the cork size from (0.5–1 mm) to (3–5 mm) as sand replacement, statistically significantly decreases the compressive strength at both 7 and 28 days based on the student's *t*-test at a 95% confidence

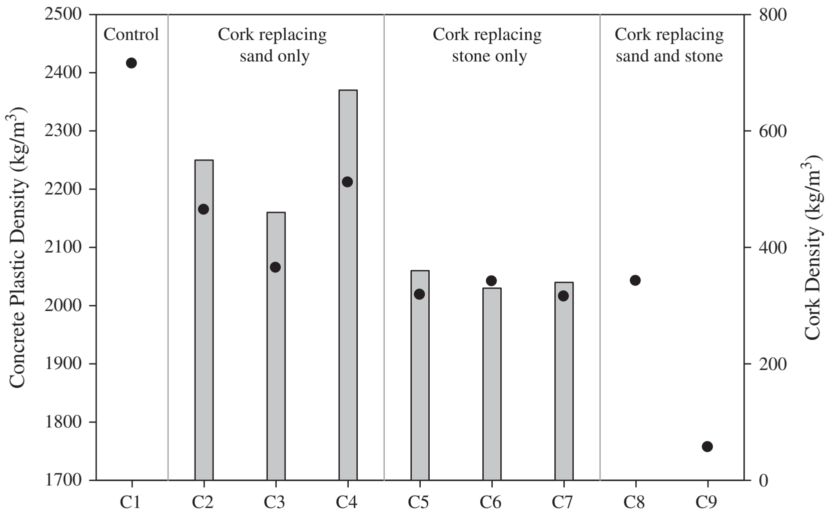

Fig. 9. Plastic density of concrete and density of cork.

level. However, comparing mixtures C5–C6, the effect of increasing the cork size from (3–8 mm) to (6–14 mm) resulted in statistically similar compressive strength measurements at days 7 and 28.

There were no beneficial or detrimental effects of concrete that containing cork of consisting of more than one size range such as mixtures, C4, C7, and C8. The mean compressive strengths of C4 were found to be statistically similar to C2 and C3. The mean compressive strength of C7 and C8 were also statistically significantly the same as C5 and C6 based on the student's *t*-test at a 95% confidence level.

The static elastic modulus results presented in Table 8, for the most part, maintain the same pattern as the compressive strength measurements. For all mixtures, the static elastic modulus increased with age, albeit in some cases only slightly. The presence of cork reduced the static elastic modulus in comparison to the control concrete, C1. The static elastic modulus is influenced greater by the percentage of cork, rather than the cork size or gradation used.

3.3.4. Rapid chloride permeability

The RCP test was conducted on two surfaces: 10 mm below the top of the cylinder and 10 mm above the bottom of the cylinder. All mixtures except one showed the bottom surface to be less permeable, as shown in Fig. 11. The specimens containing 10% cork have an RCP 44–62% greater than the top surface of the control concrete. The bottom surface of concrete containing 10% cork has a 26–53% greater RCP than the bottom surface of the control concrete, C1. This indicates that the influence of cork coarsened the pore structure and or increased the connectivity of the pore network. Closer examination of the influence of cork revealed that increasing cork size from (0.5–1 mm) in C2 to (3–5 mm) in C3 reduced the RCP. This observation was unexpected since Fig. 10 shows that C3 has a lower compressive strength compared to C2 indicating a pore structure with a higher volume of capillary pores which would be expected to increase the RCP. The MIP analysis conducted on M2 containing 10% (0.5–1 mm) cork, and M4 10% (3–5 mm) cork, did indeed show that M4 had a higher volume of capillary pores as shown in Fig. 6. Mixtures containing 20% cork resulted in a RCP value almost double that of mixtures with 10% cork. The RCP results plotted in Fig. 11 reveal that the cork size, cork gradation, and whether cork is used as sand or stone replacement or both has a less of an effect on the RCP in comparison to the percentage of cork used. Liu et al. have proposed that the permeability of lightweight concrete can be addressed by control of the cement properties and in future studies of concrete–cork composites should be addressed further [21]. The high permeability of the concrete cork composite mix designs suggests that if the material is exposed to the outdoor environment its' durability performance is expected to be relatively poor.

Table 8
Mechanical properties of concrete-cork composites at days 7 and 28.

Mix	Identification	Density (kg/m^3)		Compressive strength (MPa)				Elastic modulus (GPa)	
		7 days	28 days	7 days		28 days		7 days	28 days
		Mean*	Mean*	Mean	COV (%)	Mean	COV (%)	Mean[a]	Mean[a]
C1	Control	2461	2456	40.4	1	50.0	5	32.7	45.7
C2	10%C(0.5–l)	2219	2226	19.6	2	22.6	6	19.4	22.1
C3	10%C(3–5)	2106	2121	14.8	3	17.0	8	22.8	23.3
C4	10%CSandBlend	2230	2233	17.5	22	21.7	12	21.1	22.0
C5	10%C(3–8)	2063	2069	16.1	4	18.5	3	17.1	25.4
C6	10%C(6–14)	2071	2053	16.7	9	19.4	3	17.0	17.5
C7	10%CStoneBlend	2055	2067	15.6	2	17.8	5	20.3	21.9
C8	5%CSandBlend + 5%CStoneBlend	2084	2093	15.3	7	17.8	3	15.5	18.0
C9	10%CSandBlend + 10%CStoneBlend	1812	1823	6.6	7	7.1	5	9.3	10.8

[a] The mean is based on an average of two measurements.

* Mean is based on an average of three measurements and the COV for all mixtures is less than 1%.

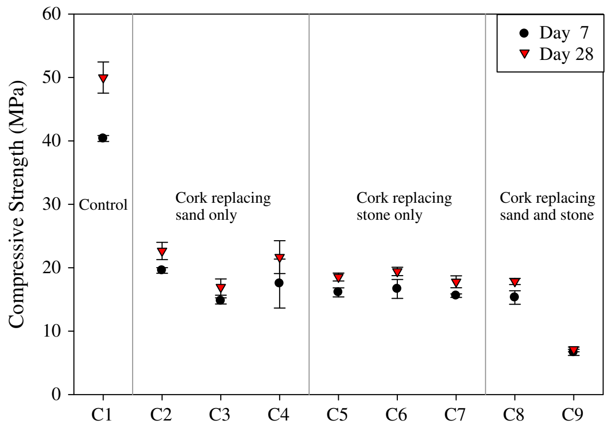

Fig. 10. Influence of cork on concrete compressive strength.

Table 9
Thermal resistance (*R*) and conductivity (*k*) (69 mm thick slabs).

Mix	Identification	*R* (m^2 K/W)	*k* (W/m K)
C1	Control	0.059	1.14
C2	10%C(0.5–1)	0.066	1.04
C3	10%C(3–5)	0.071	0.96
C4	10%CSandBlend	0.065	1.04
C5	10%C(3–8)	0.070	0.97
C6	10%C(6–14)	0.064	1.07
C7	10%CStoneBlend	0.061	1.11
C8	5%CSandBlend + 5%CStoneBlend	0.062	1.09
C9	10%CSandBlend + 10%CStoneBlend	0.086	0.79
	75 mm EPS reference	2.100	0.036

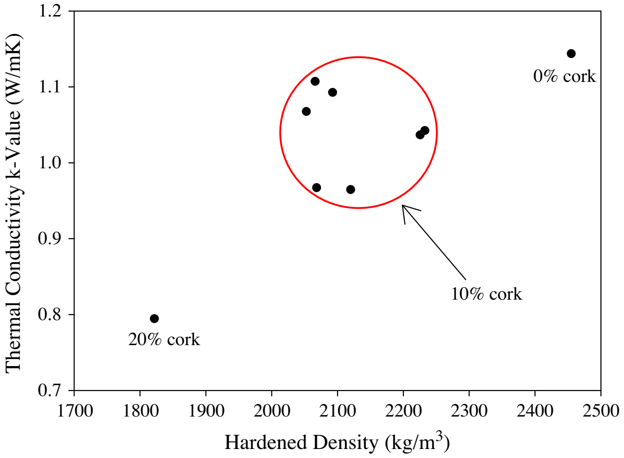

Fig. 12. Relationship between concrete hardened density and thermal conductivity.

3.3.5. Thermal resistance

The thermal resistance (*R*) and thermal conductivity (*k*) measurements for the concrete mix designs C1–C9 test measurements, and the expanded polystyrene (EPS) used to make the hot plate apparatus are presented in Table 9. The thermal resistance is a section property and the thermal conductivity is a material property and the two properties are inversely related by, $R = 1/k$, where l is the length of the heat flow path in metres. The results in Table 9 reveal that mixtures containing 10% and 20% cork, reduce the thermal conductivity compared to the control concrete, approximately 16% and 30%, respectively. The influence of cork size, or cork gradation on the thermal properties is less obvious. The relationship between the concrete hardened density and thermal conductivity of the cork–concrete mixtures, is shown in Fig. 12. A direct relationship exists between concrete density and the thermal conductivity, which is expected since trapping air in discrete pockets improves the materials insulative properties. Increasing air voids decreases the concrete density, yielding higher thermal resistance, and lower thermal conductivity. Though the results indicate that thermal conductivity increases (and resistance decreases) as density increases, the cluster of points in the 2000–2100 kg/m^3 density range shown in Fig. 12 indicates that the thermal conductivity of cork-concrete is not controlled by density alone but it is also influenced by the size and gradation of the cork. However, although there is only one data point to represent the 20% cork mixtures, the trend shows that the influence of percentage of cork has a greater impact on the thermal conductivity than cork size or gradation. This is consistent with the density measurements that are influenced greater by the cork percentage used than the cork size or cork gradation. Additional tests are required at higher cork percentages to confirm this.

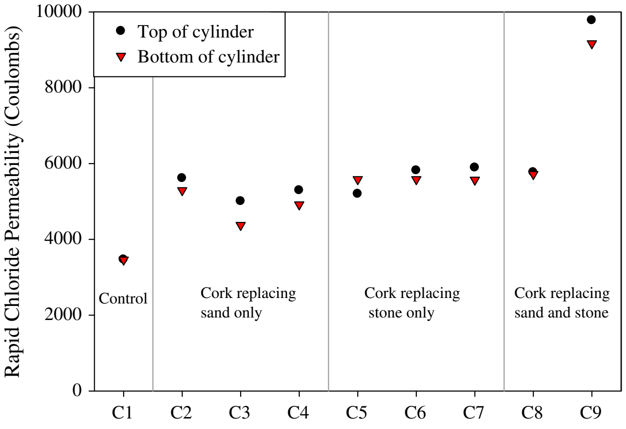

Fig. 11. Influence of cork on concrete rapid chloride permeability.

4. Outcomes and concluding remarks

From this study the following key conclusions can be drawn:

1. The exposure of waste cork to heat with increasing temperatures, namely, 50 °C and 100 °C, yields an increasingly detrimental effect on the early age compressive strength gain. In contrast, moisture saturation of waste cork prior to its use in concrete has beneficial effects on the measured compressive strength, which is attributed to the release of tannins.
2. An optimum 28 day cube strength of 24.3 MPa for cement–cork composites can be achieved with 10% of 0.5–1 mm cork granules used as sand replacement. Increasing the cork size up to 5 mm, reduces the cube strength and increases the total porosity. It is expected that the higher cube strengths is a result of a lower capillary pore volume, and a smaller interfacial transition zone.
3. The thermal conductivity of concrete–cork composites decreases, as the concrete density decreases. A 46% greater thermal resistance was measured for concrete- cork composites containing 20% cork in comparison to the concrete without cork. The thermal conductivity is controlled by the percentage of cork used which is attributed to the direct relationship observed between cork density and the concrete–cork composite density. No direct correlation between the cork size and cork gradation on the thermal conductivity was identified.

4. The percentage of cork used as sand or stone replacement has a more significant effect on the mechanical, microstructure and thermal resistance properties of concrete–cork composites than cork size or cork gradation. The hardened properties and the thermal resistance of concrete cork composites are controlled by cork density which is directly related to concrete density. The influence of cork gradation on concrete density is minimal in comparison to the percentage of cork. Consequently, no apparent benefits to the properties of concrete were observed when sand or stone blends were used over mixtures only consisting of one cork size.
5. Of the various concrete mix designs containing 10% cork, a 28 day compressive strength of 23 MPa and a 28 day static elastic modulus of 23 GPa can be achieved. This would classify the concrete–cork blend concrete as ‘normal strength concrete’ which typically ranges from 20–35 MPa. However, the rapid chloride ion permeability of concrete–cork blends examined in this study is high (>5000 Coulombs) which indicates its vulnerability to durability related degradation, and is not suitable to outdoor exposure.

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