

Investigation of the mechanical behaviour of metakaolin-based sandcrete mixtures

Panagiotis G. Asteris^{a*} , Konstantinos G. Kolovos^b, Adamantia Athanasopoulou^c, Vagelis Plevris^d and Gerassimos Konstantakatos^a

^aComputational Mechanics Laboratory, School of Pedagogical & Technological Education, Heraklion, Greece; ^bDivision of Physical Sciences & Applications, Lab of Inorganic Chemical Technology, Hellenic Army Academy, Vari, Greece; ^cFaculty of Engineering and Architecture, School of Civil Engineering, Metropolitan College, Marousi, Greece; ^dDepartment of Civil Engineering and Energy Technology, Oslo and Akershus University College of Applied Sciences, Oslo, Norway

(Received 12 February 2016; accepted 23 December 2016)

This paper investigates the mechanical properties of sandcrete mixes with metakaolin (MK) as a mineral additive. Three different types of binders were prepared: one used as reference, based on 100% w/w ordinary Portland cement (PC), and two modified, where MK replaced PC in percentages 10% or 20% by weight of the reference cement content. Experimental tests have been carried out in order to obtain the full stress–strain diagram for the material under uniaxial compressive loading. The results of the tests have been post-processed numerically in order to obtain various mechanical characteristics of the sandcrete material, such as compressive strength, modulus of elasticity and strain at maximum strength. It has been found that, in general, specimens with metakaolin in the binder exhibit enhanced compressive strength compared to the reference samples without metakaolin. The improvement in compressive strength was more pronounced in samples with higher concentration of binder (50% w/w) and low or medium water per binder (*W/B*) ratio. Samples with higher compressive strength were characterised by higher values for the measured ultrasonic pulse velocity. The strain values, recorded at maximum strength, are considerably higher than the strain value of 2‰ for concrete under uniaxial compressive load.

Keywords: sandcrete; mineral additives; metakaolin; mechanical properties; ultrasonic pulse velocity

1. Introduction

In recent years, the effects of global climate change are seriously considered to have a strong impact on mankind, affecting numerous perspectives of human life and living standard such as construction; hence, the term “sustainability” receives increasing attention (Ortiz, Castells, & Sonnemann, 2009). Investments and social responsibility are been examined and evaluated more and more with reference to their sustainability effect. It is a fact that the building industry causes a substantial percentage of the overall pollutant emissions with building activity contributing a large share of the CO₂ emissions output. For these reasons, a growing interest has arisen lately for low-cost sustainable eco-friendly construction materials originating from various resources (Lo Presti, 2013;

*Corresponding author. Emails: panagiotisasteris@gmail.com, asteris@aspete.gr

Sheen, Huang, Wang, & Le, 2014). Research has also been carried out lately on the use of recycled aggregates, sourced from construction and demolition waste, for concrete production (Silva, de Brito, & Dhiri, 2014; Behera, Bhattacharyya, Minocha, Deoliya, & Maiti, 2014; Etxeberria, Vázquez, Mari, & Barra, 2014; Evangelista & de Brito, 2014; Koenders & Enzo Martinelli, 2014; Medina, Zhu, Howind, Sánchez de Rojas, & Frías, 2014; Soares, de Brito, Ferreira, & Pacheco, 2014; Song & Ryou, 2014; Schneider, Romer, Tschudin, & Bolio, 2011; Tam, Gao, & Tam, 2005; Topçu & Firat Günçan, 1995; Xiao, Li, Corr, & Shah, 2013).

A very important material in building construction, which has been used in many developing countries, is sandcrete, mostly in the form of solid, cellular or hollow non-reinforced masonry blocks as load bearing and non-load bearing walling units (Mohammed & Cheeseman, 2011). Sandcrete belongs to a family of concretes that can be used when environmental or economic constraints limit the use of coarse aggregates. Although there is no standard definition for sandcrete, it is considered as a composite material consisting of fine aggregate (sand), ordinary Portland cement, water at an appropriate ratio and rare mineral additives (Mohammed & Cheeseman, 2011). A properly manufactured soilcrete exhibits acceptable properties for potential use in construction, such as moderate or in some cases relatively high compressive strength, low shrinkage, low thermal conductivity and high bulk density. The material can be used in the manufacture of masonry blocks and also as a binder for precast units in early stages before setting and hardening. Despite the recent advances in sandcrete technology, the use of this type of material is still limited (Denis, Attar, Breysse, & Chauvin, 2002). Kolovos, Asteris, Cotsovos, Badogiannis, & Tsivilis (2013) studied the mechanical properties of soilcrete mixtures modified with metakaolin. For the mixtures investigated, a natural clay ground soil was used as binder in moderate and low proportions in order to simulate typical mixing conditions of practice in soil stabilisation techniques. Over the last decade, a plethora of experimental (Aniculăesi, Lungu, & Stanciu, 2013; Fang et al., 2004; Omeregie & Alutu, 2006; Wenapere & Ephraim, 2009) and numerical studies (Bijan & Kaveh, 2014; Nguyen, Fatahi, & Khabbaz, 2014; Tinoco, Gomes Correia, & Cortez, 2014) have been carried out on the mechanical behaviour of cemented materials such as soilcrete and sandcrete.

In the present study, the synthesis and mechanical characteristics of an environment-friendly sandcrete material are presented, where metakaolin has been added as a mineral additive to the mix. Sandcrete mix design optimisation and mechanical behaviour of the produced samples have been experimentally investigated. It has been found that the beneficial properties of metakaolin may be used in producing sandcrete mixes with improved mechanical properties, which, provisionally, can be used as a structural material.

2. Experimental investigation

The main characteristics of the adopted research strategy simply follow those described in detail in a previous work published by the authors (Kolovos et al., 2013). Hence, the selection of the designed syntheses, the methodology for the preparation of the samples and the analytical techniques used for the characterisation of structure and mechanical properties do not differentiate in principle with those described in (Kolovos et al., 2013) and in this section, they are presented for the sake of completeness and better comprehension.

A series of cylindrical specimens with a height-to-diameter (h/d) ratio equal to 2 ($h/d = 2$) were prepared and tested under uniaxial compression in order to study the material behaviour of sandcrete and the effect of metakaolin addition in the mix.

Table 1. Chemical analysis of Portland cement and cement characteristics.

Chemical composition (% w/w)		Potential mineral composition (Bogue) (% w/w)		Physical characteristics	
SiO ₂	19.38	C ₃ S	61.06	Specific surface (cm ² /g)	3900
Al ₂ O ₃	4.26	C ₂ S	9.50	Density (g/cm ³)	3.10
Fe ₂ O ₃	3.58	C ₃ A	5.22	Water for standard consistence (%)	26.0
CaO	61.79	C ₄ AF	10.90	Autoclave expansion (%)	.08
MgO	3.35			Initial setting time (min)	110
K ₂ O	.55			Final setting time (min)	205
Na ₂ O	.15	Moduli		Heat of hydration (J/g)	330
SO ₃	3.33	LSF ^b	.97		
Cl ⁻	.00	SM ^c	2.47		
L.O.I ^a	2.05	AM ^d	1.19		
Free CaO	.86	HM ^e	2.18		

^aLOI = loss on ignition.^bLSF = lime saturation factor.^cSM = silica modulus.^dAM = alumina modulus.^eHM = hydraulic modulus.

Table 2. Chemical composition, mineralogical composition and main physical characteristics of metakaolin (MK) (Sonebi et al., 2013; Coulter & Martin, 2006).

Chemical composition (% w/w)					
SiO ₂ ^a	Al ₂ O ₃	CaO	MgO	Fe ₂ O ₃	
54.56	43.56	0.03	0.05	1.47	
Mineralogical composition (% w/w)					
Metakaolinite	Alunite	Quartz	Illite		
95.0	—	—	3.0		
Physical properties					
Specific gravity	Bulk density (kg/m ³)	Specific surface (m ² /kg)	Fineness characteristics		
			d_{20} (μm) ^b	d_{50} (μm)	d_{80} (μm)
2.50	560.7	12000	10.3	5.1	1.9

^aThe active silica content is 53% (EN 197-1, EN 196-2).^b d_i : The diameter where i % w/w of the particles (powder) are coarser.

2.1. Materials and analytical techniques

The constituents of the binder (B) used in the preparation of samples are:

- (1) Ordinary Portland Cement (PC): CEM I 42.5 N type of industrial origin according to EN 197-1 was selected for this study in order to avoid the additional influence of the presence of mineral additives found in other CEM types, to minimise water demand and to comply with requirements concerning initial strength development. Chemical analysis of Portland cement and cement characteristics are presented in Table 1 (Kolovos et al., 2013).
- (2) Metakaolin (MK): a high-purity commercial metakaolin (from Imerys Minerals) containing 95% metakaolinite (Al₂O₃·2SiO₂) (Kakali, Perraki, Tsivilis, & Badogiannis, 2001; Kolovos et al., 2013) was used. The chemical composition,

mineralogical composition and main physical characteristics of the metakaolin (MK) used are given in Table 2.

A crushed quarry sand of a limestone origin (CQLS) was selected for this study since it corresponds to a widespread typical natural rock found in a wide range of soil strata (clean sands (Pavlović, Cotsovos, Dedić, & Savidu, 2010)) that is highly erodible during jet-grouting (Pavlović et al., 2010; Pavlović, Cotsovos, Dedić, & Savidu, 2010). After sampling, according to ASTM C702 standard, crushed quarry sand was dried at 105 °C for 24 h in an electrical laboratory oven and then sieved in order to pass a 4.75-mm sieve (No. 4 according to ASTM E11 standard). The chemical composition of the CQS was derived using X-ray fluorescence (XRF) analysis, while mineralogical characteristics were determined by XRD analysis, using a Siemens D-5000 X-ray Diffractometer, with nickel-filtered Cu-K α_1 radiation ($\lambda = 1.5405 \text{ \AA}$, 40 kV and 30 mA). Chemical and mineralogical characteristics of the crushed quarry limestone sand selected are given in Table 3, while the XRD pattern for CGS is given in Figure 1. The particle size distribution for CQLS (before sieving at 4.75 mm) resulted by conducting sieve analysis, according to ASTM E11 and ASTM C136 standards. The particle size distribution graph obtained is given in Figure 2. Finally, the relative density (specific gravity) on the basis of oven-dry (OD) fine aggregate, relative density (specific gravity) on the basis of saturated surface dry fine aggregate, apparent relative density (apparent specific gravity) and water absorption of fine aggregate CQLS were measured according to ASTM C128 standard and were found to have a value of 2.73, 2.60, 2.63 and 2.05%, respectively, which are typical for a limestone crushed sand.

For the preparation of selected samples, a common superplasticizer (CHEM SLP P by Domyloco Ltd., type E and F of ASTM C494/C494M-08a) was used at appropriate percentages in order to retain high workability and optimal flow properties of the produced sandcrete.

2.2. Sampling strategy and preparation of binder types

Three different types of binders were prepared: one used as reference, based on 100% w/w ordinary Portland cement (PC), and two modified, where MK replaced PC in percentages 10% or 20% by weight of the reference cement content. Mixing was conducted in a laboratory swing mill for 1 h (no further grinding was performed) until homogeneity of the blends was achieved.

2.3. Sampling strategy and preparation of binder-ground crushed quarry limestone sand mixtures

As in the previous work (Kolovos et al., 2013), in order to simulate typical mixing conditions of practice in soil stabilisation techniques, a prior decision was taken to produce only two categories of binder-ground crushed quarry limestone sand mixtures, one that contains the binder (B) in a moderate proportion (50% w/w) and a second with a lower

Table 3. Chemical composition (% w/w) of the crushed quarry limestone sand.

SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	K ₂ O	Na ₂ O	TiO ₂	P ₂ O ₅	SO ₃	L.O.I.
5.74	2.03	46.92	.75	2.69	.24	.19	.33	.10	–	40.24

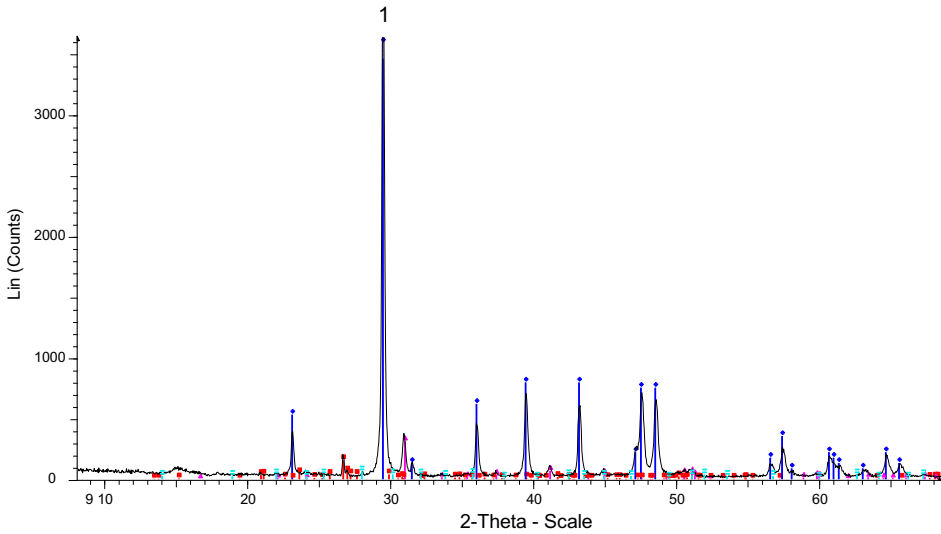


Figure 1. XRD diagram and mineralogical phases of crushed quarry limestone sand (CQLS): (1) Calcite, (2) Quartz, (3) Dolomite and (4) Anorthite.

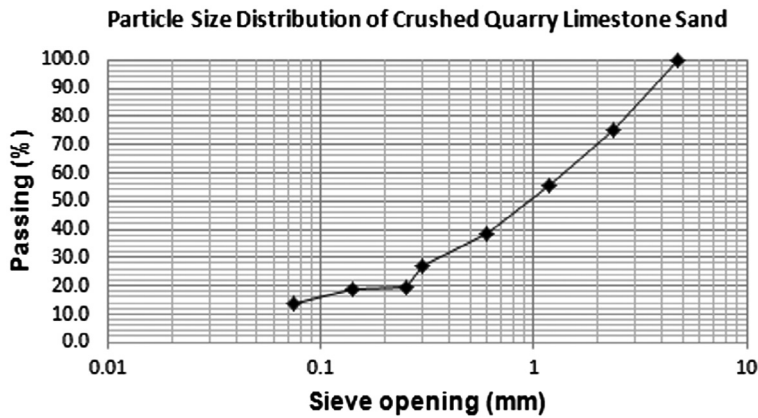


Figure 2. Particle size distribution of the crushed quarry limestone sand (CQLS), according to ASTM E11 and ASTM C136 standards.

proportion of binder (30% w/w), hence rich in crushed quarry limestone sand (70% w/w CQLS).

Thus, six binder-ground crushed quarry limestone sand mixtures were prepared by mixing CQLS with 50 and 30% w/w each one at a time of the three different types of binders.

2.4. Sandcrete preparation and properties

Sandcrete samples were prepared by mixing the six binder-ground crushed quarry limestone sand mixtures with water at 20 °C in an 80-L capacity laboratory mixer for

concrete production. All samples for every batch were prepared in two steps. Firstly, the weighted mass of sand and cement was mixed and stirred in the laboratory mixer to obtain a homogenous mixture. Secondly, the weighted mass of metakaolin (when applicable) was added to the mix. The mixing was continuous and followed the addition of water until all materials were homogeneously mixed. For syntheses that required superplasticizer, a weighted quantity was added immediately after the addition of water. The duration of the mixing was around 10–15 min.

Several trial batches were performed in order to optimise the rheological and mechanical properties. As far as the water-to-binder ratio (W/B) is concerned, according to the previous published work by the authors and relevant literature on grouting applications (Anagnostopoulos, 2007; Bouchelaghem & Almosni, 2003; Coulter & Martin, 2006; Huang, 1997; Kolovos et al., 2013; Mikkelsen, 2002; Nikbakhtan & Ahangari, 2010; Nikbakhtan, Ahangari, & Rahmani, 2010; Nikbakhtan & Osanloo, 2009; Sonebi, Lachemi, & Hossain, 2013; Tan, Zaimoglu, Hınıslıoglu, & Altun, 2005), three different values were decided in prior to be retained for all sandcrete samples: (i) a low one (L), equal to .4; (ii) a medium one (M), equal to .7; and (iii) a high one (H), equal to 1.0. Hence, three series of twelve (12) sandcrete samples at a time were obtained, with ratio $W/B = .4, .7$ and 1.0, respectively. In contrast to the soilcrete samples studied in a previous published work by some of the authors (Kolovos et al., 2013), the trial sandcrete batches – conducted with water-to-binder ratio (W/B) of .4, .7 and 1.0 – showed that no excess water is required in order to achieve the minimum appropriate workability for the produced sandcrete samples due to the substantially lower values for water absorption and humidity in crushed quarry limestone sands compared to common clay soils of high plasticity.

Using three water-to-binder ratios (W/B) and the six previously mentioned binder-ground crushed quarry limestone sand mixtures, we obtain $6 \times 3 = 18$ different types of sandcrete materials. For samples with $W/B = .40$, superplasticizer was used at appropriate percentages (2.0% w/w of the total binder weight used) in order to achieve high workability and optimal flow properties of the produced sandcrete. The codification and synthesis of sandcrete mixes are presented in Table 4.

Based on the above synthesis of the cement–sand mixes, a large number of laboratory experiments were conducted in order to support the present research. Specifically, a total of $18 \times 12 = 216$ cylindrical specimens (12 for each one synthesis) were prepared in accordance with requirements and recommendations of the ASTM standards. From the total of the 216 specimens, 144 (18×8) have been tested under uniaxial compression at 28 days in the framework of the present work, while the rest (72 specimens) are to be used in a companion, ongoing research project which aims on the estimation of the effect of metakaolin to the durability of cement–sand materials. Details for the preparation of specimens as well as for the uniaxial compression tests are given in the next section.

2.5. Determination of the mechanical properties

2.5.1. Preparation of specimens

All the specimens were cast in place in metal cylindrical molds, 100 mm (diameter) $\times$ 200 mm (height). As it is well known that the geometry of the samples affects significantly the experimental results and the measured mechanical properties, special care has been taken for finalising the samples in accordance with the requirements and recommendations of the ASTM standards. In particular, all ends of the cylinders have

Table 4. Codification and synthesis of sandcrete samples.

Sample	CEM I 42.5 N (PC) (% w/w in the dry mix)	Metakaolin (MK) (% w/w in the dry mix)	Crushed Quarry Limestone Sand (CQLS) (% w/w in the dry mix)	W/B	Superplasticizer (% w/w of the cementitious materials)
PCSA-50L	50	—	50	.4	2.0
PCSA-30L	30	—	70	.4	2.0
PMCSA10-50L	45	5	50	.4	2.0
PMCSA10-30L	27	3	70	.4	2.0
PMCSA20-50L	40	10	50	.4	2.0
PMCSA20-30L	24	6	70	.4	2.0
PCSA-50M	50	—	50	.7	—
PCSA-30M	30	—	70	.7	—
PMCSA10-50M	45	5	50	.7	—
PMCSA10-30M	27	3	70	.7	—
PMCSA20-50M	40	10	50	.7	—
PMCSA20-30M	24	6	70	.7	—
PCSA-50H	50	—	50	1.0	—
PCSA-30H	30	—	70	1.0	—
PMCSA10-50H	45	5	50	1.0	—
PMCSA10-30H	27	3	70	1.0	—
PMCSA20-50H	40	10	50	1.0	—
PMCSA20-30H	24	6	70	1.0	—

been sawed with a suitable cutting wheel according to the specifications of ASTM C39 (2000) as any irregular end surfaces or specimen axis being not perpendicular to the end faces would cause stress concentrations within the test specimen that would reduce the measured strength (Park & Suh, 2008). Specifically, all ends of the compression test specimens were made plane to within .05 mm and their deviation from perpendicularity from the axis was less than .5° (1 mm in 100 mm).

2.5.2. Compression test

Uniaxial compression tests were performed on cylinder specimens using a hydraulic four-column compression test machine (Figure 3) with a capacity ranging from 1 up to 3000 kN and the ability to adjust the loading speed. Due to the high sensitivity of the measured strength values, the machine was calibrated by a third-party certified agency before testing.

All specimens were subjected to uniaxial compression at a loading rate of .5 MPa/s and the stress–strain curves were automatically recorded. Specifically, in compliance with ASTM C469 (1994), two rigid circular rings were secured at approximately the middle one-third of the specimen height (that is the area where uniaxial compression conditions are ensured) using clamping screws, as seen in Figure 3. A linear variable differential transducer was introduced between the rings to measure the uniaxial compressive strain of the specimen at each loading step. Loading on the specimen continued at least up to the point where a 10% drop in the maximum sustained load was recorded, as depicted in Figure 4. The main results recorded were (i) the uniaxial compressive



Figure 3. Uniaxial compression test set-up.

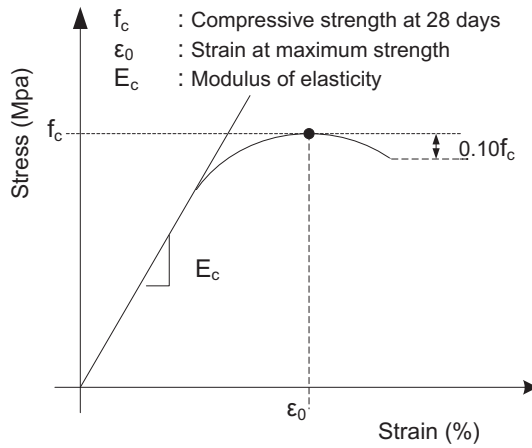


Figure 4. Stress–strain curves.

strength (f'_c); (ii) the axial strain at maximum stress (ϵ_o); (iii) the modulus of elasticity (E_c); and (iv) the full stress–strain path for the given loading.

Regarding the reliability of the uniaxial compressive strength test, it is worth mentioning that in contrast to previous similar works which did not ensure smooth, parallel and uniform bearing surfaces that are perpendicular to the applied axial load (cylinder's axis), in the present study, all specimens' stress–strain curves did not exhibit non-linearity in the initial portion of the stress–strain curve. This phenomenon of non-linearity is attributed to the irregularity of the end surfaces. In such a case, the stress–strain curves need to be modified by shifting the origin of the diagram appropriately.

3. Results and discussion

3.1. Mechanical properties of sandcrete samples

As discussed in the previous section, samples were subjected to uniaxial compression tests and the full strain–stress curves were obtained. Figures 5–10 present the stress–strain curves.

3.1.1. Compressive strength

Figure 11 presents the compressive strength (f'_c) of sandcrete samples (at 28 days) containing 30 and 50% w/w modified binder types, with the addition of 10 or 20% w/w MK, in comparison to the reference samples (binder with no addition of MK), with low (*L*), medium (*M*) and high (*H*) *W/B* ratio.

For the samples with the lower *W/B* ratio, the addition of MK in 20% by weight in the binder resulted in higher values for the average compressive strength in comparison to the reference samples. The increase in the compressive strength was 25% for sample PMCSA20-50L (in comparison to PCSA-50L) and 18% for sample PMCSA20-30L (in comparison to PCSA-30L). On the contrary, no such trend was recorded for the sample series with the addition of MK in 10% by weight in the binder. In particular, a decrease in the compressive strength was recorded for samples PMCSA10-50, while no variation was observed for samples PMCSA10-30 when compared with the reference samples (i.e. PCSA-50 and PCSA-30, respectively).

The samples with medium *W/B* ratio and the addition of MK in the binder exhibited a more pronounced increase in the compressive strength compared with the samples with low *W/B* ratio. Specifically, an increase of 26% and 53% was recorded for samples PMCSA10-50M and PMCSA20-50M, respectively, in comparison to PCSA-50M, while for samples PMCSA10-30M and PMCSA20-30M the increase in the compressive strength was 13% and 29%, respectively, when compared with the reference sample

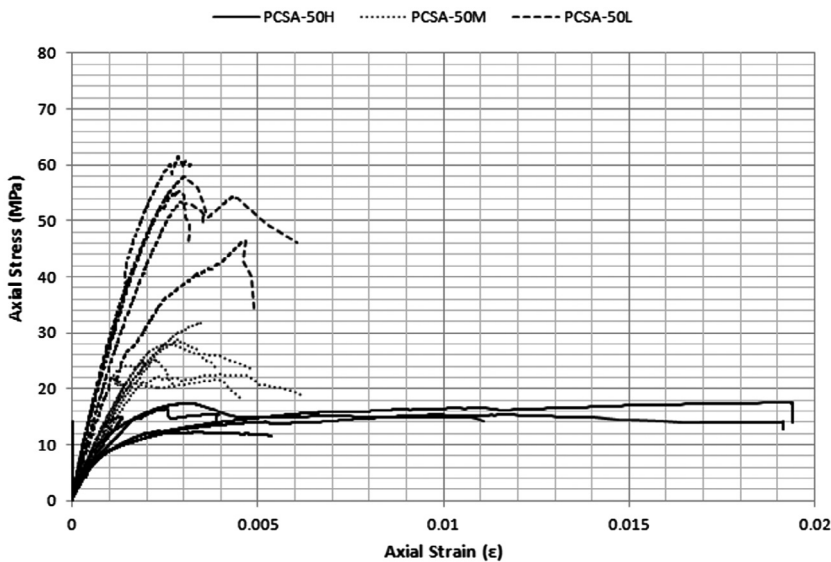


Figure 5. Stress–Strain Curve for PCSA-50 specimen series.

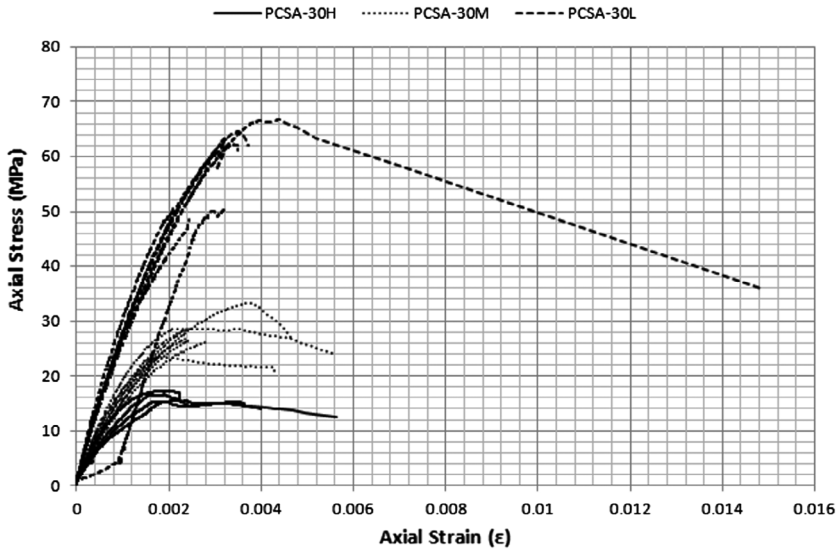


Figure 6. Stress–Strain Curve for PCSA-30 specimen series.

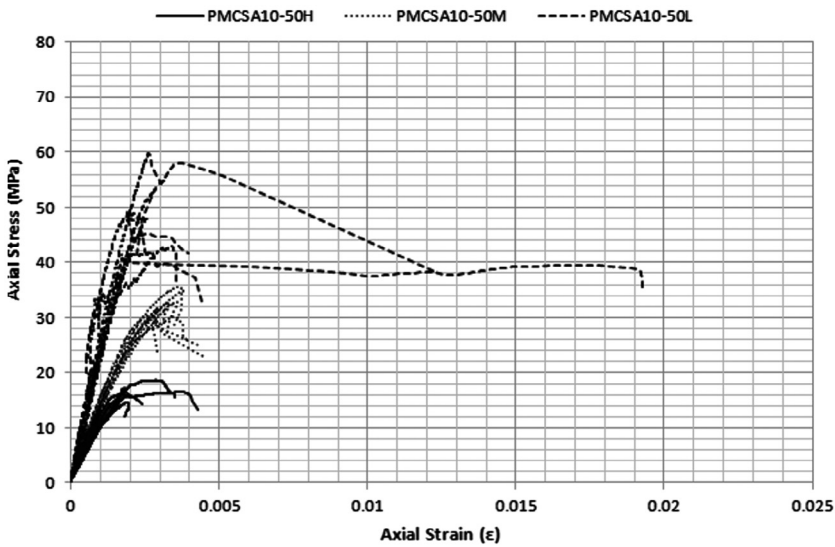


Figure 7. Stress–Strain Curve for PMCSA10-50 specimen series.

(PCSA-30M). A small increase in the compressive strength was observed in the samples with high W/B ratio and addition in 20% by weight of MK in the binder, while no variation was recorded with addition in 10% by weight of MK in the binder.

Thus, based on the observations from the compressive tests conducted, it is generally concluded that the enhancement in compressive strength (with the addition of MK) was more pronounced in samples with higher concentration of the binder and low or

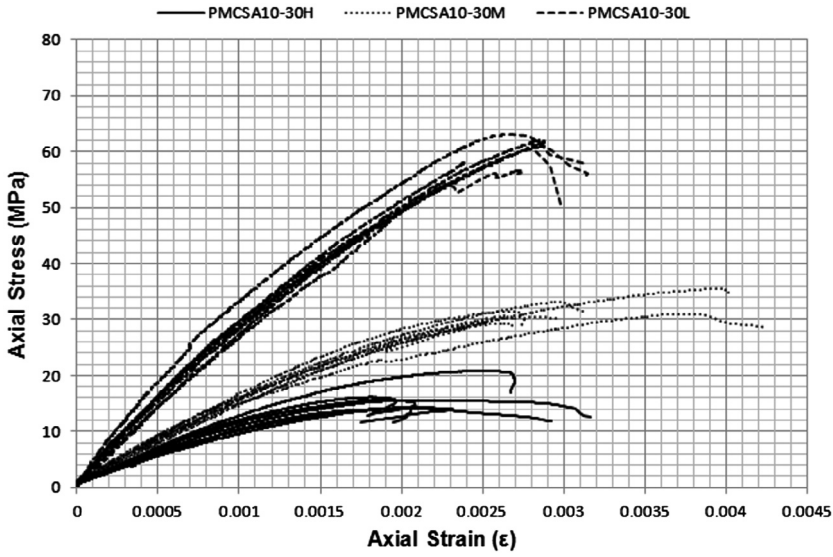


Figure 8. Stress-Strain Curve for PMCSA10-30 specimen series.

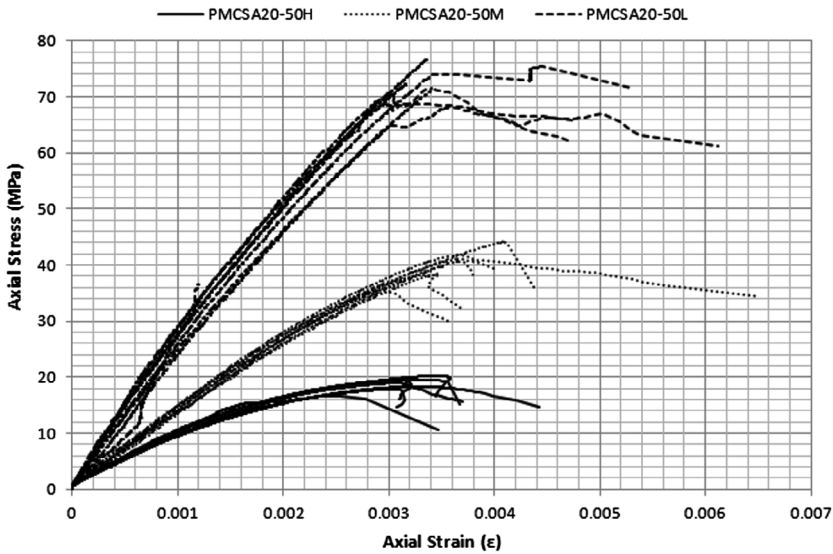


Figure 9. Stress-Strain Curve for PMCSA20-50 specimen series.

medium W/B ratio as MK exhibits a pronounced pozzolanic reactivity leading to improved compressive strength (Kostuch, Walter, & Jones, 2000). The enhancement in compressive strength with the addition of MK was also verified in an earlier study on soilcrete mechanical properties conducted by Kolovos et al. (Kolovos et al., 2013)

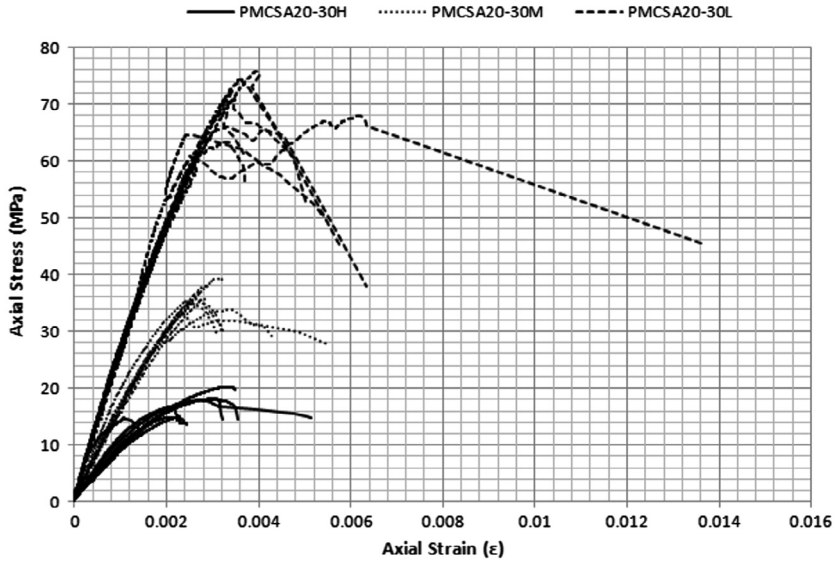


Figure 10. Stress–Strain Curve for PMCSA20-30 specimen series.

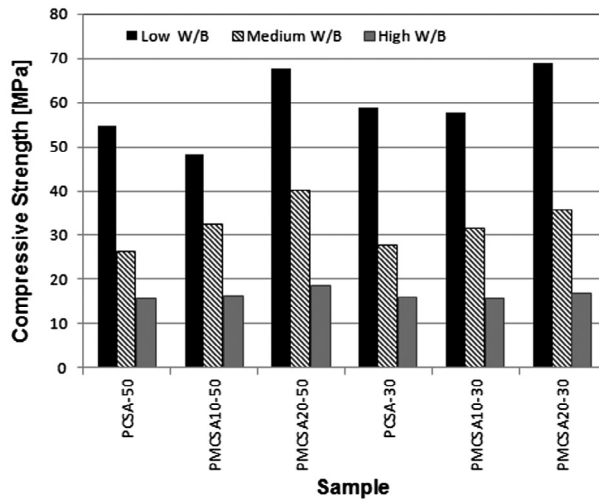


Figure 11. Compressive strength of sandcrete samples at 28 days ($W/B = .4$, $W/B = .7$ and $W/B = 1.0$).

supporting the well-reported contribution of metakaolin to concrete mixes (Nadeem, Memon, & Yiu Lo, 2013).

Figure 12 presents the relationship of compressive strength with regard to water-to-binder ratio. The decrease in the compressive strength is close to linear for the series PMCSA10-50 and PMCSA20-50 while for the rest samples, a deviation from linearity is recorded.

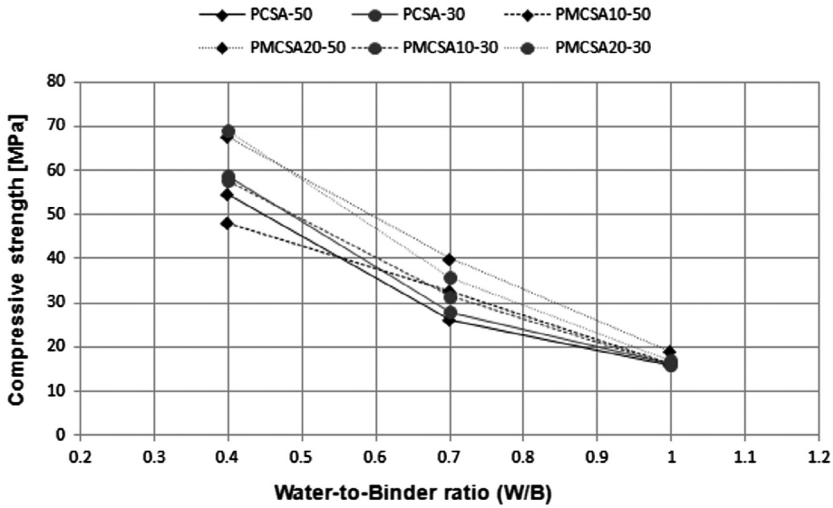


Figure 12. Average compressive strength vs. W/B ratio for all specimen series.

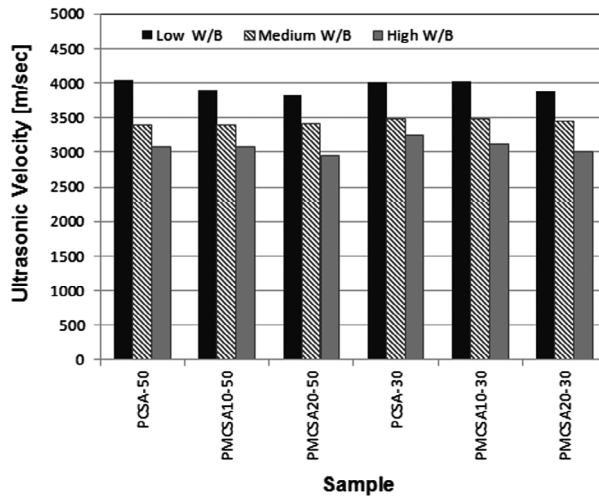


Figure 13. Measured ultrasonic pulse velocity for all specimens ($W/B = .4$, $W/B = .7$ and $W/B = 1.0$).

3.1.2. Ultrasonic pulse velocity

Prior to the compression tests, the ultrasonic pulse wave method was applied onto each specimen in order to determine the speed at which the pulse travels through the sand-concrete medium which in turn allows the determination of the dynamic elasticity modulus. Figure 13 presents the measured average ultrasonic velocity for all sample series.

As expected, the measured ultrasonic pulse velocity was higher for specimens with lower water-to-binder ratio that exhibit higher elasticity. For the specimens with higher concentration of the binder, the addition of MK in the mix resulted in lower ultrasonic

pulse velocity. With the addition of MK in the mix with lower concentration of the binder, either no variance or decrease in the ultrasonic pulse velocity was observed. As it will be explained in Section 3.1.3, lower ultrasonic velocity results in lower dynamic modulus of elasticity, i.e. increased deformability.

3.1.3. Modulus of elasticity – deformability

The average values of the elasticity modulus established experimentally for all samples were obtained from the stress–strain curves (see Figures 5–10). The experimentally established values of the elasticity modulus, calculated as the secant modulus determined from the stress–strain relationship recorded when subjecting a sandcrete cylindrical specimen to a uniaxial compressive stress approximately equal to 40% of its load-carrying capacity, are depicted in Figure 14, as average values for each type of sample. As expected, the specimens with the lowest W/B were characterised by the highest values of elasticity modulus. In particular, the experimentally established values of the elasticity module for series with low W/B ratio were found 2 and up to 2.5 times larger compared with the specimens with high W/B ratio. In contrast, for specimens with medium W/B ratio, a smaller increase in the modulus of elasticity (10–30%) was observed compared to the samples with low W/B ratio.

For the samples series with low W/B ratio, the addition of MK did not alter the elasticity modulus of the samples compared to the reference ones. The only exception to this observation was recorded in sample PMCSA10-30L with a measured elasticity modulus 15% higher than the one of the reference samples. Similarly, no significant variation in the modulus was observed for samples with high W/B ratio and 50% w/w concentration of the binder, in comparison to the reference samples, while a decrease of 23% was measured for the samples with 30% w/w concentration of the binder. For samples with medium W/B ratio, the addition of MK resulted in a decrease in the modulus of elasticity.

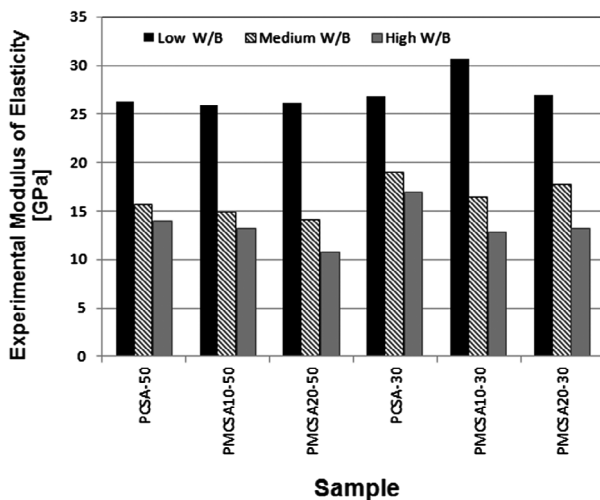


Figure 14. Modulus of Elasticity for all samples obtained from the experimentally established stress–strain curves ($W/B = .4$, $W/B = .7$ and $W/B = 1.0$).

For the samples with low and medium W/B and 50% w/w concentration of the binder, the percentage of MK in the binder (10% versus 20% w/w) showed no effect on the modulus of elasticity (i.e. specimens PMCSA10-50L and PMCSA10-50M had the same modulus of elasticity with samples PMCSA20-50L and PMCSA20-50M, respectively). The same observation is valid for samples with high W/B and 30% w/w concentration of the binder, while for 50% w/w concentration of the binder, the recorded modulus of elasticity was higher by approximately 20% for sample PMCSA10-50H compared to PMCSA20-50H.

Furthermore, based on the measured ultrasound pulse velocity, the dynamic modulus of elasticity was calculated. The relationship between the dynamic elasticity modulus and the propagation speed u_w of the ultrasonic pulse is provided by Equation (1) (Neville, 1996)

$$E_{\text{sandcrete, ult}} = \frac{\rho \cdot u_w^2 \cdot (1 + \nu)(1 - 2\nu)}{(1 - \nu)} \quad (1)$$

where ρ is the density of sandcrete and ν is the Poisson's ratio.

The average values of the dynamic elasticity modulus determined based on the ultrasonic pulse velocity method are shown in Figure 15. For the samples with low and high W/B , the addition of MK resulted in slightly lower dynamic modulus of elasticity, whereas for samples with the medium W/B , no variation was observed.

Figure 16 presents a comparison of the values of the elasticity modulus for all samples determined by the experimental stress–strain curves with its counterparts obtained by the ultrasonic pulse velocity method. As expected for cementitious materials, the value of the modulus of elasticity calculated based on the ultrasonic pulse velocity is higher than the experimentally obtained as it is associated with the material in its unloaded state. Comparing Figures 14 and 15 which show the corresponding average values, it can be seen that the values of the experimental to the dynamic modulus of elasticity ratio vary between .73 (for specimen PMCSA10-30M) and .98 (for specimen

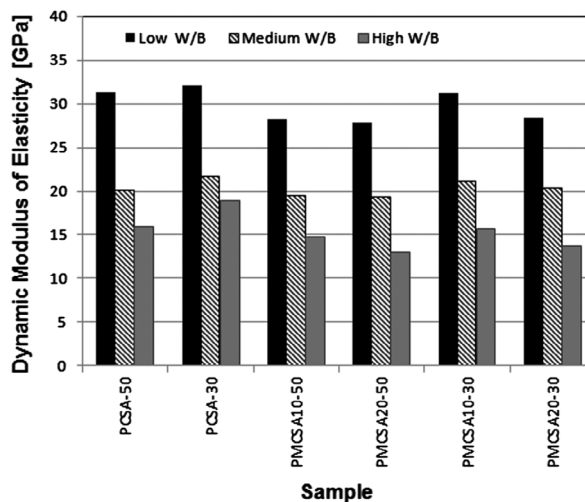


Figure 15. Dynamic Modulus of Elasticity for all samples obtained from the ultrasonic pulse method ($W/B = .4$, $W/B = .7$ and $W/B = 1.0$).

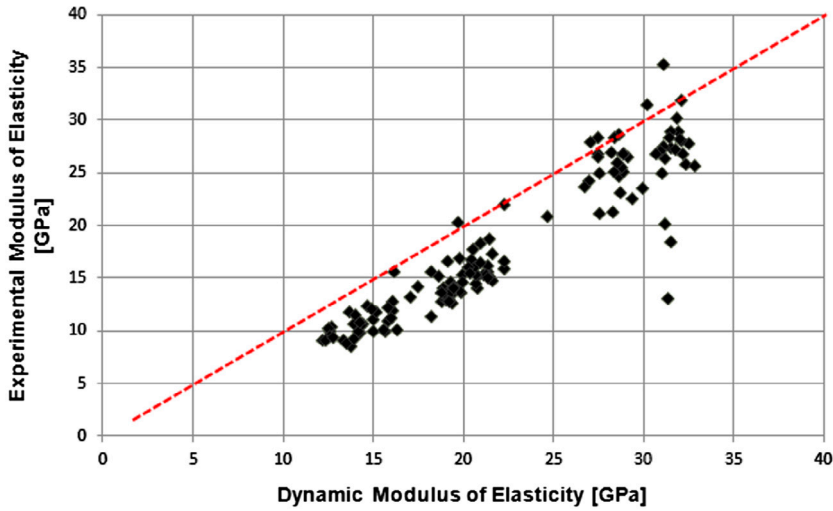


Figure 16. Comparison of Experimental and Dynamic Modulus of Elasticity for all specimens.

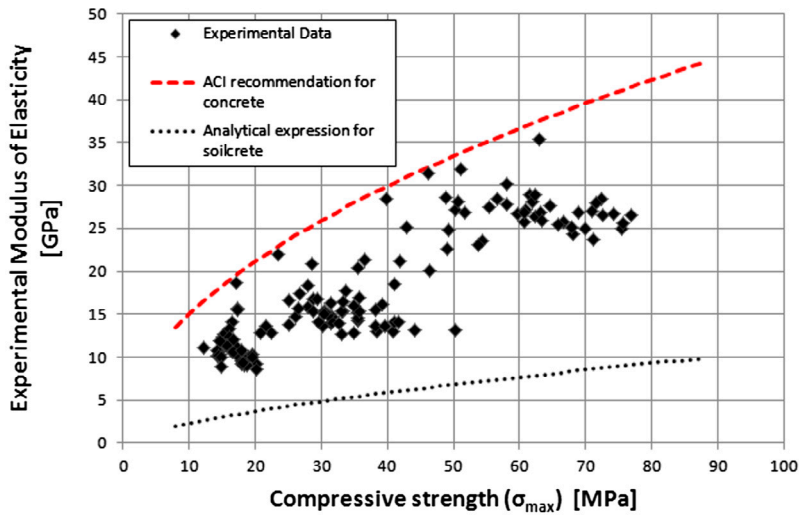


Figure 17. Experimental Modulus of Elasticity vs. compressive strength in comparison with analytical expressions for all specimens.

PMCSA10-30L). Samples with MK and low W/B ratio showed closer agreement between the elasticity module determined by the experimental stress–strain curves and the one obtained by the ultrasonic pulse velocity method.

A comparison of the values of the elasticity modulus determined from the experimental stress–strain curves of the samples with that of concrete with the same uniaxial compressive strength using the recommended formula by ACI 358- 95 (Equation 2) is given in Figure 17. The figure also presents an estimation of the elasticity modulus based on analytical formula obtained from practice (Pavlović et al., 2010) in respect to

the average value of the compressive strength of soilcrete for jet-grouting in clay layers (Equation 3):

$$E_{C(ACI)} = 4.73 \cdot f_c^{2/3} \quad (2)$$

$$E_C = 500 \cdot f_c^{0.5} \quad (3)$$

It is evident that the proposed expression for soilcrete modulus of elasticity greatly underestimates the values of the experimentally obtained modulus of elasticity of the sandcrete samples. Contrary, the recommendation by ACI gives higher values for the modulus of the sandcrete specimens in all cases.

Figure 18 shows the variation of the strain ε_o exhibited by the samples when subjected to uniaxial compressive stresses equal to their uniaxial compressive strength. Based on the values of Figure 18, it appears that ε_o varies between .0018 (for specimen PMCSA10-50H) and .0037 (for specimen PMCSA20-30L). No specific trend was observed comparing the samples with MK and the reference ones. However, in the vast majority of the samples, the strain at maximum stress is considerably higher than the strain value of .002 that concrete exhibits when subjected to its uniaxial compressive strength, confirming that sandcrete is a much “softer” material than concrete.

3.1.4. Cracking process – modes of failure

Figure 19 presents the failure modes of the sandcrete samples after the end of the compression test. During the test, visible cracks usually started from the top section of the cylinder and spread vertically downwards with increased compressive loading. The cracks enlarged and extended downwards rapidly during the final stages of the experiment and no definite sign was observed before the collapse.

It is understood that microcracks develop during the hardening phase of sandcrete samples inside the cylindrical mould because of the different effects in shrinkage

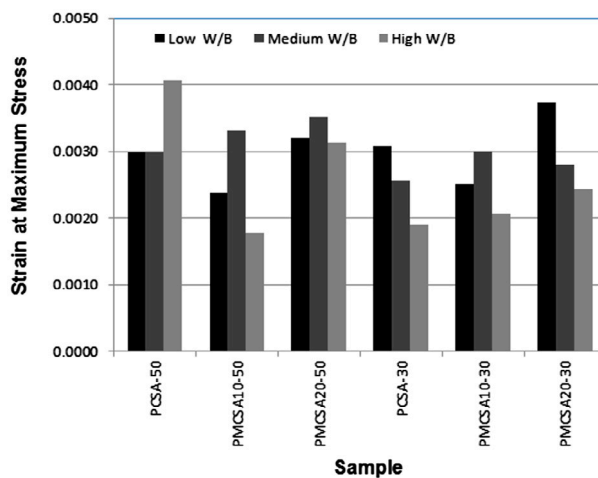


Figure 18. Strain exhibited by specimens when subjected to uniaxial compressive stress equal to their uniaxial compression strength for all specimen series.

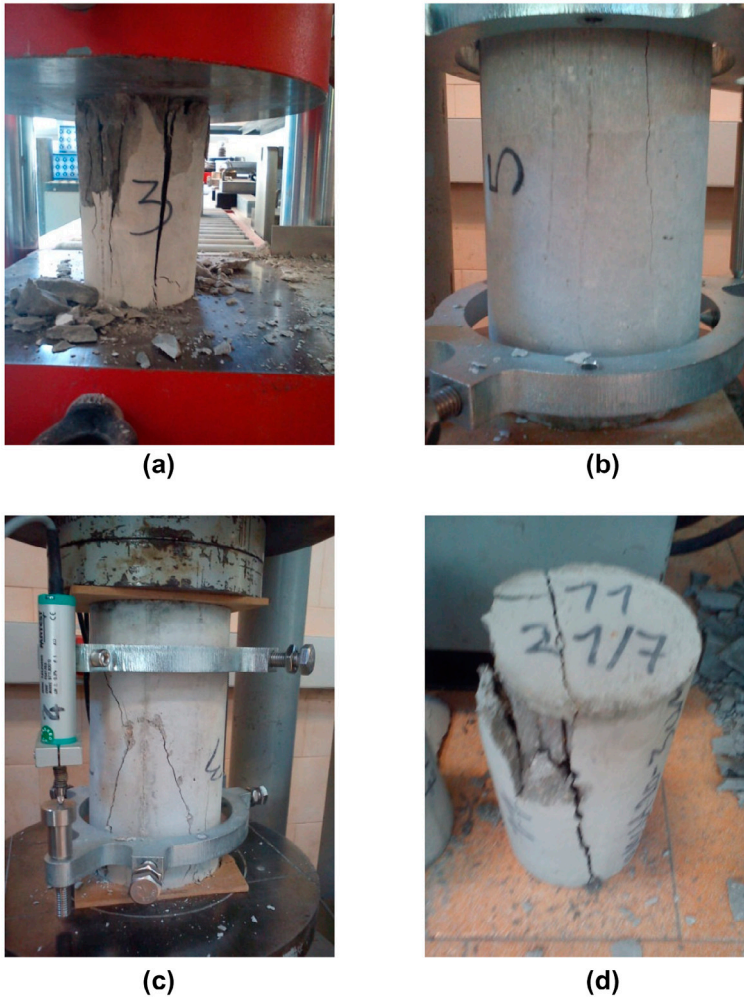
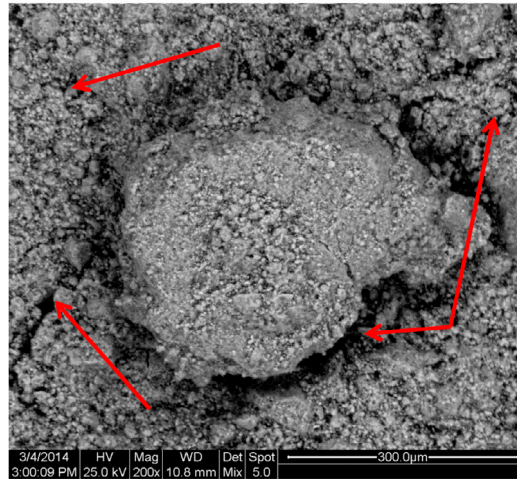


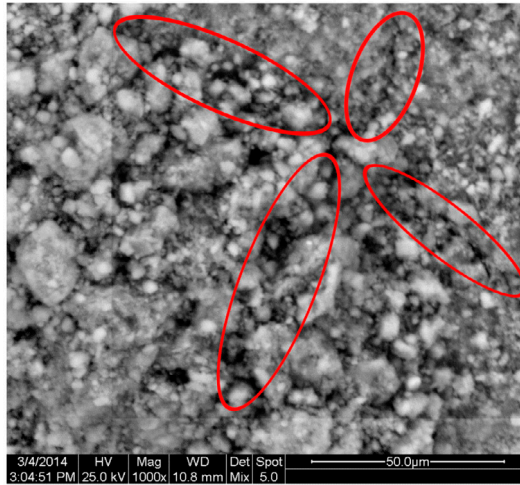
Figure 19. Failure modes of selected plain sandcrete cylinders at maximum compressive loads: PMCSA10-30H (a), PMCSA10-50H (b), PMCSA10-30M (c) and PMCSA20-30M (d).

exhibited by both sand and cement. It is worth noting that the evaluation of the SEM micrographs of samples indicates the presence of microcracks in the interface between sand grains and cement hydrates (Figure 20). An adequate number of microcracks were observed in the case of samples doped with metakaolin – these samples were characterised by brittle failure and higher ultimate compressive strength values.

During the tests, at approximately 80% of the maximum compressive load, a slight noise was noticeable from inside the cylinder. This suggested that microcracks had enlarged and spread in the sandcrete medium. As the load reached the ultimate load, a very strong noise accompanied the failure of the cylinder specimens. It is noted that the cracking pattern in the sandcrete samples, in terms of crack width and length, is significantly extended when compared with plain concrete. As a result, during testing of the sandcrete samples, a high amount of energy is stored and suddenly released at failure, accompanied by a strong noise.



(a)



(b)

Figure 20. SEM photos of fractured sandcrete samples showing the development of microcracks: PMCSA20-30H (a) & (b).

The salient characteristic of all forms of failure in sandcrete samples, in contrast with the failure types observed in the classical case of plain concrete with aggregate, is that all cracks are straight with smooth surfaces due to the absence of aggregates. According to Walraven (1980, 1981), the aggregate interlock mechanism is directly related to the way in which a crack is formed in concrete. As the strength of the hardened cement paste is generally lower than the strength of the aggregate particles, cracks intersect the cement paste but run along the edges of the aggregate particles. Thus, the aggregate particles, extending from one crack face, “interlock” with the opposite face and resist shear displacements.

As regards the morphology, the observed forms of failure of the samples can be grouped in two categories. The first type of failure includes sandcrete specimens whose cracks are vertical (Figure 21). This is in accordance with the columnar type of failure type described by the ASTM standards (ASTM C873/C873M-15, 2015) and it appears in specimens with low water-to-binder ratio, especially those with the highest percentage of metakaolin characterised by the higher compressive strength (as discussed in Section 3.1.1). For this group of samples, it was observed that the cracks usually started somewhere near the centre of the cylinder and extended towards the edges of the specimens.

The second type of observed failure type includes sandcrete specimens with medium W/B ratio whose cracks are not vertical (Figure 22). In particular, it includes all other observed types (cone, cone and split and cone and shear based on ASTM failure-type classification (ASTM C873/C873M-15, 2015). Observation revealed that the cracks

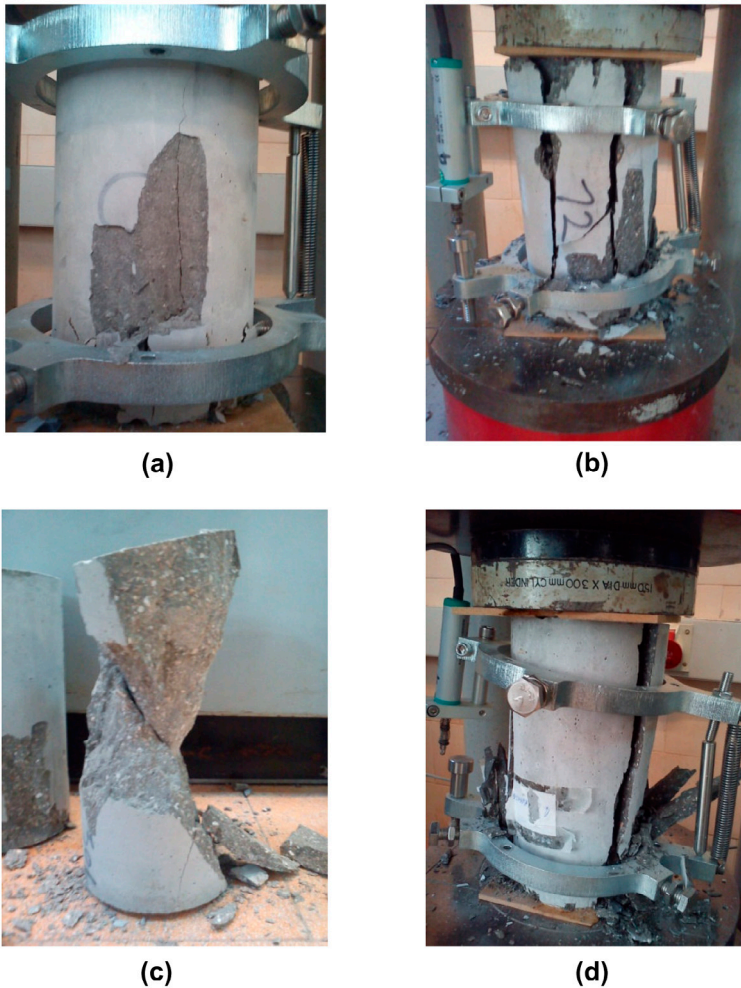


Figure 21. Failure of selected specimens with low W/B ratio: PMCSA10-50H (a), PMCSA10-50L (b), PMCSA20-30L (c) and PMCSA20-50M (d).

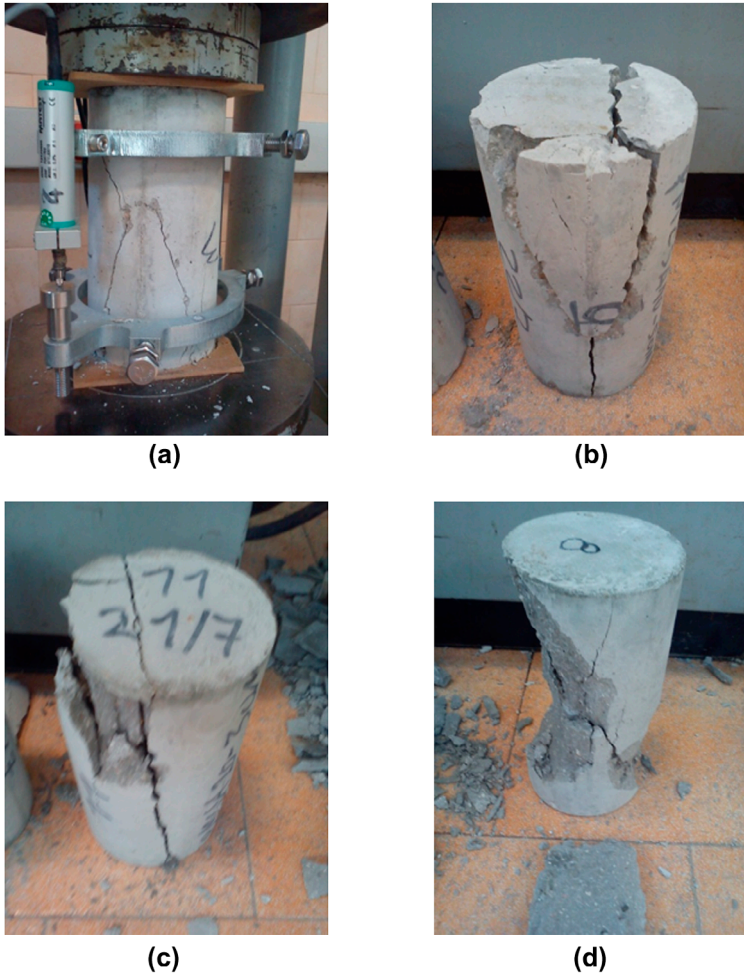


Figure 22. Failure of selected specimens with low W/B ratio: PMCSA10-30M (a), PMCSA10-50M (b), PMCSA20-30M (c) and PMCSA20-50M (d).

usually started at the top section of the cylinder and spread downwards with increased compressive load.

4. Conclusions

The present study investigates the mechanical properties of sandcretes produced by the addition of 10 and 20% w/w metakaolin in the designed binder types. The main conclusions from the study are given below

- In general, the addition of metakaolin has produced an improvement of the mechanical properties of the material. Specimens with MK in the binder exhibit enhanced compressive strength compared to the reference samples. The improvement in compressive strength was more pronounced in samples with higher

concentration of binder (50% w/w) and low or medium W/B ratio. Lower or no significant strength increase was observed in the case of sandcrete samples with lower concentrations of binder.

- Samples with higher compressive strength were characterised by higher values for the measured ultrasonic pulse velocity. The highest ultrasonic pulse velocity was obtained for samples with low W/B ratio.
- The experimentally established modulus of elasticity was 2 up to 2.5 times larger for specimens with low W/B ratio compared to specimens with high W/B ratio. In samples with low W/B ratio, the addition of MK did not alter the modulus of elasticity compared to the reference ones.
- The ratio of the experimental modulus of elasticity obtained from the stress–strain curve and the dynamic modulus of elasticity was found to vary between .73 and .98. Samples with MK and low W/B ratio showed close agreement between the elasticity module determined by the experimental stress–strain curves and the dynamic modulus of elasticity. In all samples, the values of dynamic modulus were found higher than their experimental counterparts.
- The proposed equation for soilcrete underestimated, in a significant way, the value of the experimentally established modulus of elasticity. On the other hand, the ACI-proposed equation for concrete gives higher values for the modulus of elasticity in all samples.
- In all samples, the strain values, recorded at maximum strength, are considerably higher than the strain value of .002 that concrete exhibits when subjected to a uniaxial compressive test.
- All samples with low W/B ratio exhibited columnar type of failure – this type of failure was particularly pronounced in samples with high percentage of MK in the binder. Samples with medium W/B ratio were characterised by various types of failure, namely: cone, cone and split and cone and shear.

Based on the above findings, an in-depth research project is in progress aiming to investigate the influence of metakaolin on the durability of cemented materials such as the soil and sandcrete ones as well as to the further assessment of its effectiveness based on terms of fracture toughness.

Acknowledgements

The authors would like to express their special thanks to TITAN Cement Company S.A. for the free supply of cement as well as to Imerys Minerals Ltd for providing the amounts of metakaolin used in this work. The authors would also like to express their gratitude to Mr Ch. Psaromichelakis, Mr M. Frantzis, Mr I. Karampampas, Mr P. Kalantzakis and Mr V. Christopoulos for their assistance on the preparation of samples and also to Dr Ch. Leptokaridis and Dr D. Fragoulis from TITAN Cement Company S.A. for the compressive strength and the XRD tests of samples, respectively.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Panagiotis G. Asteris  <http://orcid.org/0000-0002-7142-4981>

References

- Anagnostopoulos, C. S. (2007). Cement-clay grouts modified with acrylic resin or methyl methacrylate ester: Physical and mechanical properties. *Construction and Building Materials*, 21, 252–257.
- Aniculăeși, M., Lungu, I., & Stanciu, A. (2013). Some effects of eco-cement stabilization of expansive soils on critical state parameters. *Environmental Engineering and Management Journal*, 11, 769–778.
- ASTM C39/C39M-14. (2000). Standard test method for compressive strength of cylindrical concrete specimens, *Annual Book of ASTM Standards*, 4, 24–29.
- ASTM C469-94. (1994). *Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression*. ASTM Standards, p. 4.
- ASTM C873/C873M-15. (2015). *Standard test method for compressive strength of concrete cylinders cast in place in cylindrical molds*. West Conshohocken, PA: ASTM International. Retrieved from www.astm.org
- Behera, M., Bhattacharyya, S. K., Minocha, A. K., Deoliya, R., & Maiti, S. (2014). Recycled aggregate from C&D waste & its use in concrete – A breakthrough towards sustainability in construction sector: A review. *Construction and Building Materials*, 68, 501–516.
- Bijan, E., & Kaveh, A. (2014). A novel approach in estimation of the soilcrete column's diameter and optimization of the high pressure jet grouting using adaptive neuro fuzzy inference system (ANFIS). *Open Journal of Geology*, 4, 386–398. Article ID: 48998. doi:10.4236/ojg.2014.48030
- Bouchelaghem, F., & Almosni, A. (2003). Experimental determination of the longitudinal dispersivity during the injection of a micro-cement grout in a one-dimensional soil column. *Transport in Porous Media*, 52, 67–94.
- Coulter, S., & Martin, C. D. (2006). Single fluid jet-grout strength and deformation properties. *Tunnelling and Underground Space Technology*, 21, 690–695.
- Denis, A., Attar, A., Breysse, D., & Chauvin, J. J. (2002). Effect of coarse aggregate on the workability of sandcrete. *Cement and Concrete Research*, 32, 701–706.
- Etxeberria, M., Vázquez, E., Mari, A., & Barra, M. (2014). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and Concrete Research*, 37, 735–742.
- Evangelista, L., & de Brito, J. (2014). Concrete with fine recycled aggregates: A review. *European Journal of Environmental and Civil Engineering*, 18, 129–172.
- Fang, Y.-S., Kuo, L.-Y., & Wang, D.-R. (2004). Properties of soilcrete stabilized with Jet grouting. In *Proceedings of the Fourteenth International Offshore and Polar Engineering Conference – ISOPE*, Toulon, France, May 23–28, pp. 696–702.
- Huang, W. H. (1997). Properties of cement-fly ash grout admixed with bentonite, silica fume, or organic fiber. *Cement and Concrete Research*, 27, 395–406.
- Kakali, G., Perraki, T., Tsvivilis, S., & Badogiannis, E. (2001). Thermal treatment of kaolin: The effect of mineralogy on the pozzolanic activity. *Applied Clay Science*, 20, 73–80.
- Koenders, E. A. B., & Enzo Martinelli, M. P. (2014). Compressive strength and hydration processes of concrete with recycled aggregates. *Cement and Concrete Research*, 56, 203–212.
- Kolovos, K. G., Asteris, P. G., Cotsovos, D. M., Badogiannis, E., & Tsvivilis, S. (2013). Mechanical properties of soilcrete mixtures modified with metakaolin. *Construction and Building Materials*, 47, 1026–1036.
- Kostuch, J. A., Walter, G. V., & Jones, T. R. (2000). High performance concretes containing Metakaolin – a review. In *Proceedings of the International Conference – Concrete 2000* (Vol. 2, pp. 1799–1811). Dundee, UK.
- Lo Presti, D. (2013). Recycled tyre rubber modified bitumens for road asphalt mixtures: A literature review. *Construction and Building Materials*, 49, 863–881. doi:10.1016/j.conbuildmat.2013.09.007
- Medina, C., Zhu, W., Howind, T., Sánchez de Rojas, M. I., & Frías, M. (2014). Influence of mixed recycled aggregate on the physical-mechanical properties of recycled concrete. *Journal of Cleaner Production*, 68, 216–225.
- Mikkelsen, P. E. (2002). Cement–bentonite grout backfill for borehole instruments. *Geotechnical Instrumentation News*, 20, 38–42.
- Mohammed, B., & Cheeseman, C. R. (2011). Use of oil drill cuttings as an alternative raw material in sandcrete blocks. *Waste and Biomass Valorization*, 2, 373–380.

- Nadeem, A., Memon, S. A., & Yiu Lo, T. (2013). Mechanical performance, durability, qualitative and quantitative analysis of microstructure of fly ash and Metakaolin mortar at elevated temperatures. *Construction and Building Materials*, 38, 338–347.
- Neville, A. M. (1996). *Properties of concrete* (4th ed.). Harlow: Addison Wesley Longman.
- Nguyen, L. D., Fatahi, B., & Khabbaz, H. (2014). A constitutive model for cemented clays capturing cementation degradation. *International Journal of Plasticity*, 56, 1–18. doi:10.1016/j.i-jplas.2014.01.007
- Nikbakhtan, B., & Ahangari, K. (2010). Field study of the influence of various jet grouting parameters on soilcrete unconfined compressive strength and its diameter. *International Journal of Rock Mechanics and Mining Sciences*, 47, 685–689.
- Nikbakhtan, B., Ahangari, K., & Rahmani, N. (2010). Estimation of jet grouting parameters in Shahriar dam. *Iranian Journal of Science and Technology*, 20, 472–477.
- Nikbakhtan, B., & Osanloo, M. (2009). Effect of grout pressure and grout flow on soil physical and mechanical properties in jet grouting operations. *International Journal of Rock Mechanics and Mining Sciences*, 46, 498–505.
- Omoregie, A., & Alutu, O. E. (2006). The influence of fine aggregate combinations on particle size distribution, grading parameters, and compressive strength of sandcrete blocks. *Canadian Journal of Civil Engineering*, 33, 1271–1278.
- Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, 23, 28–39. doi:10.1016/j.conbuildmat.2007.11.012
- Park, Y. S., & Suh, J. K. (2008). Comparative study on compressive strength of concrete with new sand-cap and neoprene pad. *International Journal of Concrete Structures and Materials*, 2, 15–19.
- Pavlović, M. N., Cotsovos, D. M., Dedić, M. M., & Savidu, A. (2010). Reinforced jet-grouted piles. Part 1: Analysis and design. *Proceedings of the Institution of Civil Engineers-Structures B*, 163, 299–308.
- Pavlović, M. N., Cotsovos, D. M., Dedić, M. M., & Savidu, A. (2010). Reinforced jet-grouted piles. Part 2: materials and tolerances. *Proceedings of the Institution of Civil Engineers-Structures B*, 163, 309–315.
- Schneider, M., Romer, M., Tschudin, M., & Bolio, H. (2011). Sustainable cement production – present and future. *Cement and Concrete Research*, 41, 642–650.
- Sheen, Y. N., Huang, L. J., Wang, H. Y., & Le, D. H. (2014). Experimental study and strength formulation of soil-based controlled low-strength material containing stainless steel reducing slag. *Construction and Building Materials*, 54, 1–9.
- Silva, R. V., de Brito, J., & Dhir, R. K. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Materials*, 65, 201–217. doi:10.1016/j.conbuildmat.2014.04.117
- Soares, D., de Brito, J., Ferreira, J., & Pacheco, J. (2014). Use of coarse recycled aggregates from precast concrete rejects: Mechanical and durability performance. *Construction and Building Materials*, 71, 263–272.
- Sonebi, M., Lachemi, M., & Hossain, K. M. A. (2013). Optimisation of rheological parameters and mechanical properties of superplasticised cement grouts containing metakaolin and viscosity modifying admixture. *Construction and Building Materials*, 38, 126–138.
- Song, I. H., & Ryou, J. S. (2014). Hybrid techniques for quality improvement of recycled fine aggregate. *Construction and Building Materials*, 72, 56–64.
- Tam, V. W. Y., Gao, X. F., & Tam, C. M. (2005). Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. *Cement and Concrete Research*, 35, 1195–1203.
- Tan, O., Zaimoglu, A. S., Hınıslıoglu, S., & Altun, S. (2005). Taguchi approach for optimization of the bleeding on cement-based grouts. *Tunnelling and Underground Space Technology*, 20, 167–173.
- Tinoco, J., Gomes Correia, A., & Cortez, P. (2014). Support vector machines applied to uniaxial compressive strength prediction of jet grouting columns. *Computers and Geotechnics*, 55, 132–140.
- Topçu, B., & Firat Günçan, N. (1995). Using waste concrete as aggregate. *Cement and Concrete Research*, 25, 1385–1390.

- Walraven, J. C. (1980). *AGGREGATE INTERLOCK: A theoretical and experimental analysis* (PhD thesis). Delft Institute of Technology, Delft.
- Walraven, J. C. (1981). Fundamental analysis of aggregate interlock. *ASCE Journal of the Structural Division*, 107, 2245–2270.
- Wenapere, D. A., & Ephraim, M. E. (2009). Physico-mechanical behaviour of sandcrete block masonry units. *Journal of Building Appraisal*, 4, 301–309.
- Xiao, J., Li, W., Corr, D. J., & Shah, S. P. (2013). Effects of interfacial transition zones on the stress–strain behavior of modeled recycled aggregate concrete. *Cement and Concrete Research*, 52, 82–99.