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The effect of wollastonite powder with pozzolan micro silica in conventional concrete containing recycled aggregate

Du Dinh-Cong[1,2a], Mohammad. H. Keykhosravi[3b], Rayed Alyousef[4c], Musab N.A. Salih[5d], Hoang Nguyen[*6], Hisham Alabduljabbar[4e], Abdulaziz Alaskar[7f], Fahed Alrshoudi[7g] and Shek Poi-Ngian[8h]

[1]Division of Construction Computation, Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[2]Faculty of Civil Engineering, Ton Duc Thang University, Ho Chi Minh City, Viet Nam
[3]Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia
[4]Department of Civil Engineering, College of Engineering, Prince Sattam bin Abdulaziz University, Al-kharj 11942, Saudi Arabia
[5]School of Civil engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia
[6]Institute of Research and Development, Duy Tan University, Da Nang 550000, Viet Nam
[7]Department of Civil Engineering, College of Engineering, King Saud University, Riyadh 11362, Saudi Arabia
[8]Construction Research Center (CRC), Institute for Smart Infrastructure & Innovative Construction (ISIIC), School of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

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Abstract. Construction development and greenhouse gas emissions have globally required a strategic management to take some steps to stain and maintain the environment. Nowadays, recycled aggregates, in particular ceramic waste, have been widely used in concrete structures due to the economic and environmentally friendly solution, requiring the knowledge of recycled concrete. Also, one of the materials used as a substitute for concrete cement is wollastonite mineral to decrease carbon dioxide (CO2) from the cement production process by reducing the concrete consumption in concrete. The purpose of this study is to investigate the effect of wollastonite on the mechanical properties and durability of conventional composite concrete, containing recycled aggregates such as compressive strength, tensile strength (Brazilian test), and durability to acidic environment. On the other hand, in order to determine the strength and durability of the concrete, 5 mixing designs including different wollastonite values and recovered aggregates including constant values have been compared to the water - cement ratio (w/c) constant in all designs. The experimental results have shown that design 5 (containing 40% wollastonite) shows only 6.1% decrease in compressive strength and 4.9% decrease in tensile strength compared to the control plane. Consequently, the use of wollastonite powder to the manufacturing of conventional structural concrete containing recycled ceramic aggregates, in addition to improving some of the properties of concrete are environmentally friendly solutions, providing natural recycling of materials.

Keywords: wollastonite powder; recycled concrete; ceramic waste; durability in the acidic environment

1. Introduction

Concrete as an important construction material has been widely applied in concrete structures (Shariati 2008, Luo *et al.* 2019, Xie *et al.* 2019) with an application range from roads, tall buildings to dams and etc. (Nguyen-Sy *et al.* 2017, Trung *et al.* 2019, Xu *et al.* 2019, Arani *et al.* 2019, Nosrati *et al.* 2018b, Sajedi and Shariati 2019). Concrete as a composite material has comprised various preparation levels, depending on its application, say high strength concrete (Arabnejad Khanouki *et al.* 2011, Shariati *et al.* 2011b, Shariati *et al.* 2012a, Shariati *et al.* 2012c, Shariati *et al.* 2012d, Shariati 2013, Mohammadhassani *et al.* 2014a, Mohammadhassani *et al.* 2014b, Mohammadhassani *et al.* 2014c, Shariati 2014, Shariati *et al.* 2014a, Shariati *et al.* 2014b, Khorramian *et al.* 2015, Shariati *et al.* 2015, Khanouki *et al.* 2016, Shahabi *et al.* 2016, Shariati *et al.* 2016, Khorramian *et al.* 2017, Nguyen-Sy *et al.* 2017, Hosseinpour *et al.* 2018, Nasrollahi *et al.* 2018, Ziaei-Nia *et al.* 2018a) or light weight concrete (Shariati *et al.* 2010, Hamidian *et al.* 2011, Shariati *et al.* 2011a, Shariati *et al.* 2011c, Shariati *et al.* 2012b, Shariati *et*

*Corresponding author, Ph.D.
E-mail: nguyenhoang23@duytan.edu.vn
[a] Ph.D.
E-mail: dinhcongdu@tdtu.edu.vn
[b] MS.C.
E-mail: mohammad.key1996@gmail.com
[c] Ph.D.
E-mail: r.alyousef@psau.edu.sa
[d] Ph.D. Candidate
E-mail: nasmusab2@live.utm.my
[e] Ph.D.
E-mail: h.alabduljabbar@psau.edu.sa
[f] Ph.D.
E-mail: abalaskar@ksu.edu.sa
[g] Ph.D.
E-mail: falrshoudi@ksu.edu.sa
[h] Ph.D.
E-mail: shekpoingian@utm.my

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al. 2017, Vo-Duy *et al.* 2017, Ho-Huu *et al.* 2018, Davoodnabi *et al.* 2019). Application of concrete with its special properties has been extended to few more usages like pavement and roads (Gerami *et al.* 2008, Kheyroddin 2008a, Kheyroddin 2008b, Sharbatdar 2008, Toghroli *et al.* 2017, Bazzaz 2018, Bazzaz *et al.* 2018, Li *et al.* 2019). Nowadays, few more studies have been performed to produce concrete via different modern, old and waste materials (Winter and Henderson 2003, Toghroli *et al.* 2018a, Toghroli *et al.* 2018b, Li *et al.* 2019), as a reasonable method for surviving the earth from non-recyclable materials.

In the ceramic industry, about 5-10% of production in different processes has led to the waste materials that could be decreased in the case of new technology usage for new units. Later the mentioned wastes (ceramic industry) have been accumulated in the nearby area, leading to the environmental pollution and affecting the life and agriculture lands. Thereafter, using recycled materials in construction of new concrete has certainly protected the natural resources (Pratik D Viramgama 2016). On the other hand, different phenomena such as earthquakes, floods and storms, as well as human disasters like wars have caused the structures' destructions including concrete structures (Shima *et al.* 2005, Vo-Duy *et al.* 2015, Abedini *et al.* 2017, Akhoundan *et al.* 2018). Thus, the volume of debris remained from these degradations has been steadily increased, signifying the issue of landfill of damaged concrete, considering that one of the main solutions to reduce the destructive environmental effects (burying), due to the worn concrete, has been highlighted in degraded material's recycling (Nagataki *et al.* 2004).

Supplementary powders in concrete mixes as either metakaolin, fly ash, ground granulated blast-furnace slag, perlite, rice husk ash, or mineral pozzolans such as wollastonite, pumice, and limestone have been investigated by previous studies. Hence, the obtained results could be used in reinforced concrete, composite steel-concrete, and high-performance concrete. Though using wollastonite and recycled aggregates in concrete have been proved as an eco-efficient approach, these minerals and recycled additives do not affect the compressive strength and flexural strength. In this case, pozzolans and reproduced aggregates could be used in a variety of applications not only as pavement and pervious concrete additives but also as the in situ concrete supplement or concrete-filled steel tubes and composite dampers (Suhatril *et al.*, Arabnejad Khanouki *et al.* 2010, Daie *et al.* 2011, Sinaei *et al.* 2011, Jalali *et al.* 2012, Ghassemieh and Bahadori 2015, Bahadori and Ghassemieh 2016, Khorramian *et al.* 2016, Shah *et al.* 2016, Shahabi *et al.* 2016, Tahmasbi *et al.* 2016, Heydari and Shariati 2018, Ismail *et al.* 2018, Wei *et al.* 2018, Zandi *et al.* 2018, Abedini *et al.* 2019, Li *et al.* 2019, Milovancevic *et al.* 2019, Shi *et al.* 2019). Also, the soft computing and numerical analyses have been proposed and carried out along with many experimental studies; thus, the novel hybrid and artificial intelligence algorithms could be used in these applications (Shao and Vesel 2015, Khorami *et al.* 2017, Sedghi *et al.* 2018, Shao *et al.* 2018, Shariat *et al.* 2018, Katebi *et al.* 2019, Shariati *et al.* 2019, Trung *et al.* 2019).

Moreover, the experimental tests have extracted the mechanical and chemical properties of the concrete produced by cement replacement, recycled coarse, and fine aggregates. Therefore, according to the reported results and observations about the advantages and disadvantages of these types of concretes, researchers can use these materials to address some shortcomings in the lateral and seismic behavior of steel frames, steel tubular structures, and pallet rack systems (Kazerani *et al.* 2014, Shah *et al.* 2015, Khorami *et al.* 2017, Najarkolaie *et al.* 2017, Shariati *et al.* 2018, Chen *et al.* 2019, Shao *et al.* 2019, Shi *et al.* 2019).

Regarding all the benefits of recyclable aggregates, only little percentage of destructive concrete is used as recycled aggregate in new construction. The combination of polymer, silica fume and rubber aggregates from rubber tire particles to obtain an optimized PC has resulted that PC with silica fume, polymer and rubber aggregate replacement to mineral aggregate has greater compressive and flexural strength (Hamidian *et al.* 2011, Li *et al.* 2019). The amount of construction and material production from the waste materials has been significantly raised in the last few years. The recovery and recycling of materials are necessary resulted from the natural resources and from the lack of discarded material's usage. In Iran, due to the growing construction of residential buildings, and the requirement of reconstruction in trading- dealing sector, the resources of natural aggregates have been reduced while the structural debris has been raised. Accordingly, only in Tehran/ Iran, 12 million metric tons of scum has been produced in 2001. This is not the case if the recycled materials are feasible. In this study, waste ceramic has been used in concrete. The replacement percentage of recycled aggregates has reduced the compressive strength, tensile strength and elastic modulus and a decrease in carbonation and erosion. On the other hand, Wollastonite is a neutral material with high elasticity modulus including a needle-shaped crystalline structure and formed by the interaction of limestone with silica in hot earth pits during the reaction

$$\mathbf{Sio_2+caoco_3 \longrightarrow casio_3+co_2}$$

This material has been applied to reduce the cracks of building, to improve the elasticity of plastic products, dentistry, sand blasting or polishing, wall covering, and generally in ceramic or tile manufacturing due to its white and needle-shaped components. Wollastonite has mightily been replaced to limestone and sand in glass fibers to improve the surface conditions (Kalla *et al.* 2015). Thus, the use of this material as a pozzolan in concrete has improved the applicability of concrete. Also, the use of wollastonite in concrete has reduced the water absorption and contraction in concrete samples and increased the durability against sulfate attack (Mathur *et al.* 2007b). The results of another research has shown that using 2% wollastonite strands has made the highest toughness (increasing the resistance to failure due to stress), which is 80% more than normal Portland cement, however, if the volume of the strands has reached to 3 to 5%, toughness has been raised by the porosity increment (Low and Beaudoin 1993b, Low and Beaudoin 1994, Shariati *et al.* 2011d, Nosrati *et al.* 2018a). Based on the Colin *et al.* (1999) reports, the flexural

Table1 The physical properties of cement

Property	Density (g/cm^3)	special surface Blaine (cm^2/g)	28-day compressive strength (MPa)	Accumulated density (g/cm^3)
Amount	3.14	3475	41.6	1.15

Table 2 Chemical analysis of cement

Oxide forming cement	Portland cement type 2
Cao	63.61
Al_2o_3	4.5
Fe_2o_3	3.19
Sio_2	21.2
Mgo	2.05
So_3	2.86
Na_2+k_2o	1.09
Loi	1.5

Table 3 Ingredients of powdered wollastonite

Cao,%	Cl,%	So_3,%	P_2o_5,%	Sio_2,%	Al_2o_3,%	Mgo,%	Na_2o,%	Zno,%	Cuo,%
49.8	0.089	0.032	0.14	30.7	0.5	4.6	0.064	0.005	0.02
Nio,%	Co_3o_4,%	Fe_2o_3,%	Mno,%	Cr_2o_3,%	V_2o_5,%	Bao,%	Y_2o_3,%	Sro,%	
0.008	0.007	5.5	0.18	0.018	0.005	0.089	0.002	0.013	

strength of the concrete has been increased by the use of wollastonite including gray metal or silica soot (McKenney *et al.* 1999).
The strength and permeability of wollastonite with concrete (Chad 2010) have resulted that the compressive and flexural strength of concrete are raised by the replacement of 15% cement by wollastonite.

In other research, Soliman and Nehdi (2014) have examined the effect of a potent concrete shrinkage of wollastonite powder over the strength of concrete shrinkage, resulting in that the use of wollastonite in concrete has initially increased the compressive strength of the concrete, however, reduced the porosity of concrete, making the contraction in concrete (Soliman and Nehdi 2014).

2. Lab program

2.1 Consumables

The materials of this study have included cement, sand, gravel, super lubricant, wollastonite, recycled micro silica and recycled aggregates as follows:

2.1.1 Cement

The cement used in the construction of concrete roads, docks, and bridges has been hardened both in the air and water when its physical strength has been increased like the cement Hydraulics known as Portland cement. According to ASTM standard, the minimum 28-day compressive strength of a cement is 25 kg/mm^2 equals to 250 kg/m^2 (Standard 2007). In addition, total Cao and Sio_2 oxide in Portland cement should be at least 50%. In this study, the cement type 2 is moderate anti-sulfate cement with an average hydration whose physical properties and chemical analysis are presented in Tables 1 and 2.

2.1.2 Microcilica

The use of micro-silica in concreting adjacent to the sea coast has recently been considered in engineering.

Fig. 1 Wollastonite powder consumed

Fig. 2 Recycled aggregates

Fig.3 Concrete samples inside and outside of frame

Due to its prominent characteristics, microsilica application for improving the mechanical properties and increasing the durability of concrete in advanced countries has been increased. Microsilica, a suitable cement material in concrete, is a subset of arc furnaces in production of Ferro-silicon alloys as highly polystyrene with more than 90% silica and a non-crystalline state with an extremely thin fineness of particles and an average diameter of 0.1 microns. Technical specification of powdered microcrystalline cellulose has i included the physical state as Pozzolanic powder, color as light gray, and particle shape as spherical and non-crystalline (amorphous).

2.1.3 Wollastonite powder

The wollastonite of the test (this study) has been gained in a workshop of Knowledge Base of Tiva Trade Mahan in Isfahan, Iran. The gradients of the wollastonite used in this study are presented in Table 3. This powder is also, shown in Fig. 1.

2.1.4 A Review of Wollastonite applications

Wollastonite with an essentiality in the global industry has been used in ceramic tile manufacturing, regarding its whiteness, main components' releasing of volatility and its needle shape. Additionally, wollastonite is used in paper manufacturing, tint and vinyl tile. In plastic, Wollastonite has increased the strength of the composition due to its needle structure. Also, the electrical insulation characteristic of wollastonite has raised the fire resistance. The production of mineral wool insulation and decorative construction materials is another usage of wollastonite in industry [60]. In wollastonite chemical formula, depending on the crystallization type, there are three types of structural changes as 1) commonly wollastonite is wollastonite (1A) occurred in a therapeutic device, 2) Wollastonite (2M) or paraulostonite, consolidation in the monoclinic and 3) wollastonite (7A) or cw-wollastonite device is also intricate in the tertiary clinic, but the shape of the crystals is different from type one (1A) (Nikonova *et al.* 2003). This mineral is based on calcium isosilicate, containing iron and magnesium (Mathur *et al.* 2007a).

Wollastonite is extracted as a white powder with a length ratio to various diameters. Microfiber wollastonite (WMFs) is much cheaper than steel and carbon fibers. The microfiber has a length of 0.4-0.6 mm and a diameter of 25-150 micrometers. The highest length available in this fiber is 20: 1 (Low and Beaudoin 1993a, Nikonova *et al.* 2003).

2.1.5 Aggregates consumed

In this study, the gravel is 4.75 to 19 mm broken, its

Table 4 A mix design of this study

Weight unit (kg/m^3)								Ratio of water to cement (w/c)	Mix design
Super fluent	Fine grain	recycled aggregate	Natural aggregate	wollastonite	microsilica	water	cement		
10	700	410	410	0	10	176	400	0.4	[1]SCW_0
10	700	410	410	10	10	176	360	0.4	SCW_{10}
12	700	441010	410	20	10	176	320	0.4	SCW_{20}
12	700	410	410	30	10	176	280	0.4	SCW_{30}
15	700	410	410	40	10	176	240	0.4	SCW_{40}

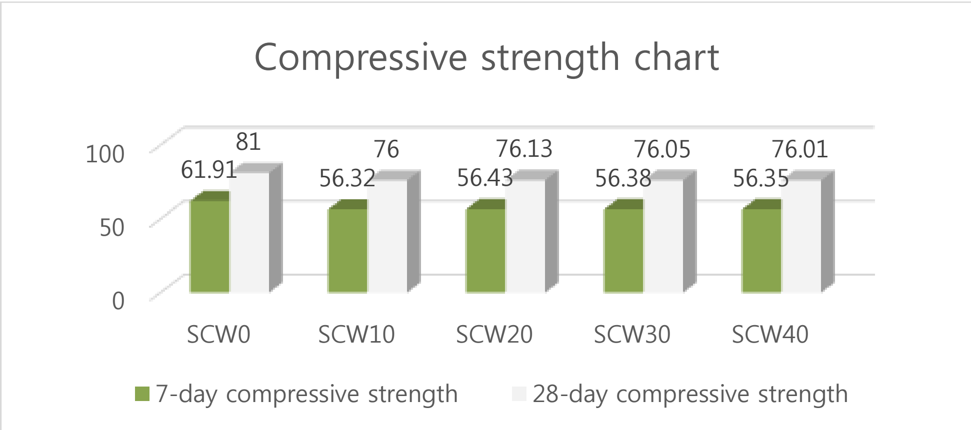

Chart 1 Compressive strength variations

Fig. 4 Failure of cubic sample under compression

largest dimension is 19 mm and its density is 2650 Kg/m^3. Applied sand is a 5-0 river flushed one produced from the Sofeh mine in Isfahan, Iran. The specific gravity of this sand is 2750 Kg/m^3.

2.1.6 Recycled aggregates

In this research, ceramic waste is used as recycled aggregates collected from the rubble and put on the Los Angeles machine to be tested. (Fig. 2)

2.1.7 Super plasticizer

Super-plasticizers are made according to the requirements of ASTM-C494 TYPE A & F standard, making the dispersion of cement in concrete mixes while creating more contact with water that causes better hydration. Accordingly, in long term, the resistance of this concrete is made of concrete with the same water-to-cement ratio and no additive will be more. Water-reduction additives have increased the impregnability of concrete against water and chemical solution, increasing the durability of concrete. In other words, these materials might be prepared by concrete manufacturers and prefabricated concrete units for efficient and cost effective production used when the high ductility of concrete and the increment

Table 5 Compressive strength results for 7&28-day

28-day compressive strength (Mpa)	7-day compressive strength (Mpa)	Design properties
81	61.91	SCW_0
76	56.32	SCW_{10}
76.13	56.43	SCW_{20}
76.05	56.38	SCW_{30}
76.01	56.35	SCW_{40}

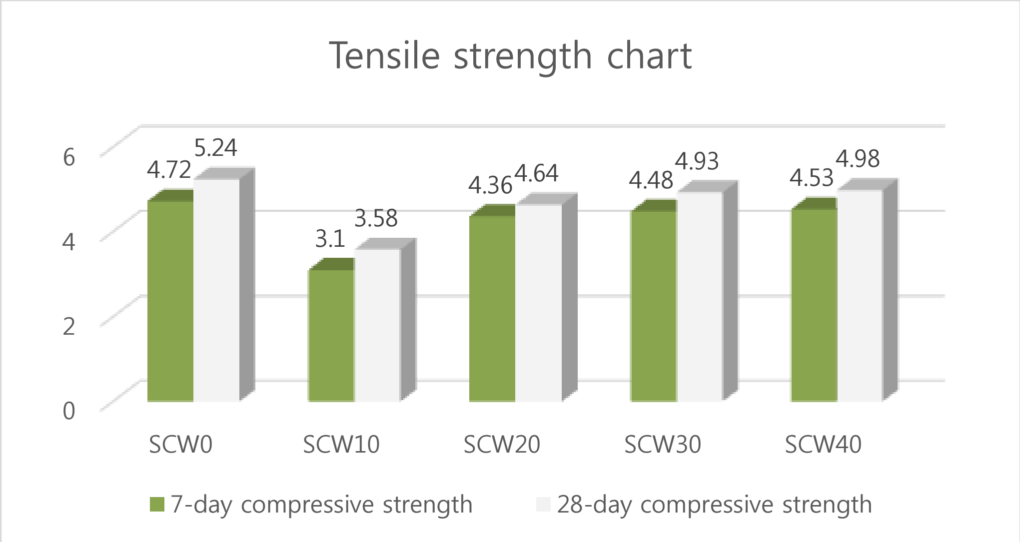

Chart 2. Tensile strength variations

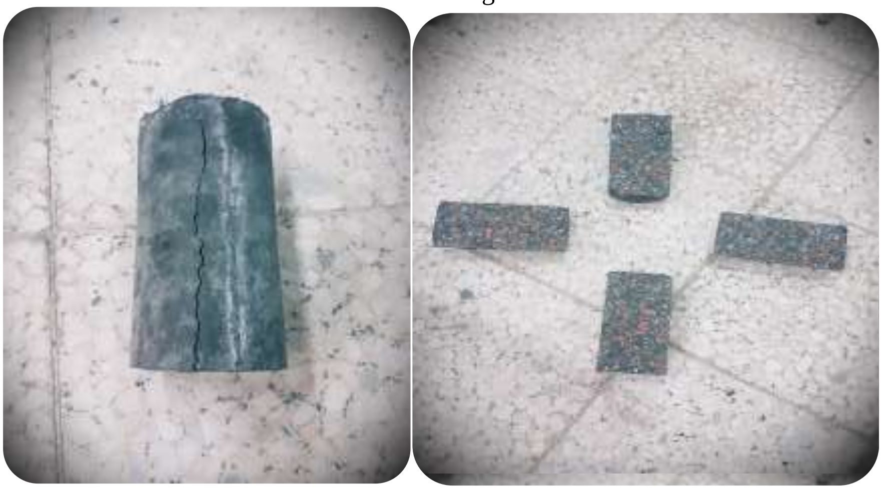

Fig. 5 Sample failure under stretching

of initial and final strength of concrete are applied. Noting that these products are greatly effective in reducing water, so that when used as a water-reduction agent for concrete in standard amount, it has simply reduced the water consumption by 18% and 20%. Respectively, in some specific concrete cases and using conventional values, water could be at most reduced by 40%. Also, more lubricated properties of these materials can lead to a high, fluid and self-aligned concrete. The applicability of this concrete is highly segregated than the conventional concrete, so that the concrete is minimized by reducing the operation and vibration, or even by itself while the water consumption is decreased. One of the Super-plasticizers is polycarboxylate, light brown with a specific weight (gr/cm^3) of 1.06 and a PH of 8.

2.2 Mix design

High performance concrete (HPC) has relied on different parameters such as cement type, aggregate and water reducer amount (Ziaei-Nia *et al.* 2018b).

Table 6 Tensile strength results for 7&28-d

28-day compressive strength (Mpa)	7-day compressive strength (Mpa)	Design properties
5.24	4.72	SCW_0
3.58	3.10	SCW_{10}
4.64	4.36	SCW_{20}
4.93	4.48	SCW_{30}
4.98	3.53	SCW_{40}

Table 7 Comparison of sample weight changes before and after entering the acidic environment

Average weights of specimens after exposure to acidic medium	Average weights of specimens before exposure to acidic medium	Design number
2405	2412	SCW_0
2394	2406	SCW_{10}
2426	2438	SCW_{20}
2410	2422	SCW_{30}
2415	2427	SCW_{40}

Also, decision variables, input and output variables, objective function and constraints have been demonstrated, while proposing a dynamic optimization model addressed by the empirical results.

The main mixture has consisted of aggregate, recycled aggregate, microsilica, wollastonite powder, type 2 cement and water, creating a good balance between the components mix design. The mix design (experimental variables) of this study is shown in Table 4. Mixing and curing are performed based on ASTM C192 standard (Concrete and Aggregates 2007). Total number of samples for this study is 15 (5 cylinders as 200×100 mm and 10 cube samples as 100×100×100 mm). Fig. 3 shows cylindrical and cubic specimens. All specimens are compressed in each bundle of concrete with a round head bar 25 times in 3 layers expelled from the mold for 24 hours and entered the curing stage until the desired age.

3. Experimental results and discussion

3.1 Compressive strength test

The sample type has affected the compressive strength of concrete. The 28-day compressive strength of the cylindrical specimens is about 80% of the cube's compressive strength (150 mm) and about 83% of cube samples' compressive strength (200 mm).

The compressive strength to test method is presented by ASTM C39 standard in a concrete breaker jack, subsequently, 10×10×10 cubic samples after treatment are removed from the cold water pond and placed under a hydraulic jack and their compressive strength has been investigated at different ages. Table 5 and chart 1 show the results of the compressive strength of 7-day and 28-day prepared specimens.

Based on the results, the amount of wollastonite and recycled aggregate are obviously regarded as an important variable in compressive strength. Design 1 (no wollastonite) and recycled aggregate have shown a compressive strength of 81 MPa, while design 5 (containing 40% wollastonite) and recycled aggregates have shown only 6.1% drop in strength. Fig. 4 shows the failure shape of specimen under the uniaxial compressive test.

3.2 Tensile strength test (Brazilian test)

Calculation of tensile strength of concrete is performed in two ways:

1-Tensile strength under a direct pull

2-Tensile strength due to bending

Tensile strength is different in two states and in the first case, the tensile strength is lower. In the first case, for cylindrical samples, the specimen is placed on the side and placed under the pressure of the jack machine to defeat the specimen, generally testing Fusion of cylindrical specimens or Brazilian experiments.

Tensile strength is calculated according to the ASTM C496 standard and used in the Brazilian frame and Concrete breaker jack to break it. Table 6 and chart 2 show of the tensile strength of 7-day and 28-day prepared specimens. Fig. 5 shows the failed samples under stretching due to applied tensile force.

3.3 Durability test in acidic condition

Though, concrete structures are designed and built for a period of 50 years, in some cases, due to the hydrochloric acid invasion, these structures have been destroyed after a few years. Therefore, the study of concrete in terms of weight and strength is important when exposed to the acidic environment. Hence, in this study, for each mixing plan,

Table 8 Comparison of compressive strength changes of samples in normal and acidic medium

Percentage of compressive strength reduction during 28 days	28-day compressive strength of the sample after exposure to the acidic medium	28-day compressive strength of the sample after exposure to the normal medium	Design number
3.58 %	78.1	81	SCW_0
3.57 %	73.28	76	SCW_{10}
6.30 %	71.33	76.13	SCW_{20}
6.90 %	70.8	76.05	SCW_{30}
9.9 %	68.47	76.01	SCW_{40}

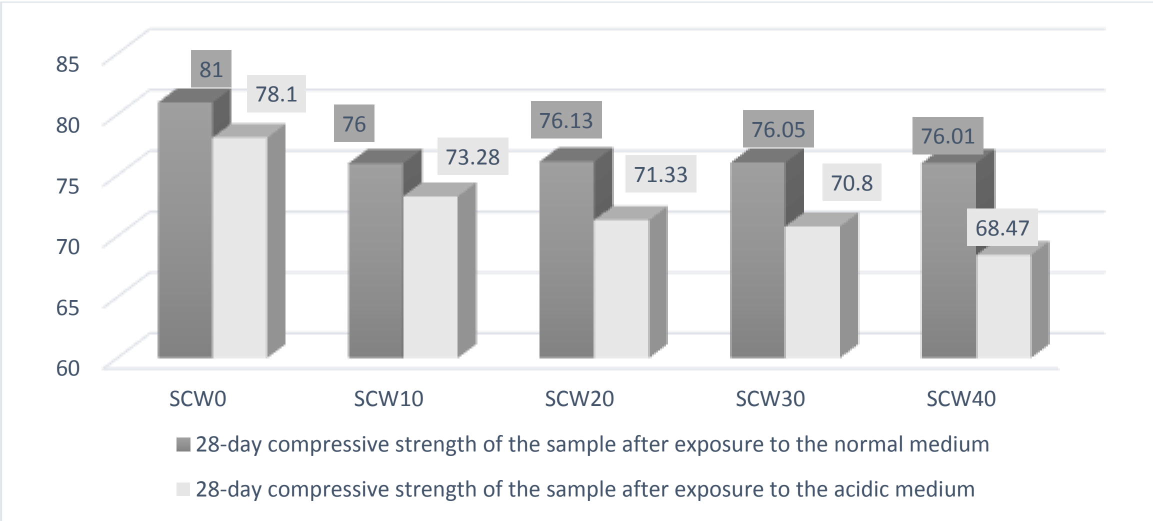

Chart 3. Characterization of compressive strength values in normal and acidic environments

two 10 cubic meters with a curing period of 28 days have been exposed to medium acid medium pH = 2 hydrochloric acids for 28 days. The purpose of this study is to compare the weight and compressive strength of the samples before and after the exposure to the acidic medium.

3.4 Experiment to determine the variation of sample weight in hydrochloric acid solution

In order to investigate the effect of hydrochloric acid on samples, changes in weight and compressive strength variations have been measured on concrete samples. Thereafter, samples have been treated with hydrochloric acid solution at pH = 2 after 28 days of treatment. The degree of acidity of the solution is controlled by using pH meter and, if necessary, adjusted to pH 2 with hydrochloric acid. Regarding the samples' weight variation, the weight of the specimens has been measured before and after the exposure to acidic medium. The results of this review are as presented in Table 7.

The test has been carried out on 10 cubic samples with 10 cm per side (from each mix design of two specimens in an acidic environment) as described above. According to the results, the corrosion rate of the sample in the acidic medium has been raised by the raise of wollastonite powder amount. In other words, by the increment of clastic wollastonite, the weight of the specimens has been decreased but in negligible weight loss. The reason for this is that the hydrochloric acid solution has dissolved the surface layer, also by destroying this layer and washing it, the weight of the samples has been reduced. But in the meantime, the better the surface layer of the concrete, the stronger its permeability.

3.5 Experiment to determine the compressive strength variations of concrete samples in hydrochloric acid solution

A compressive strength test has been carried out on concrete specimens placed in a hydrochloric acid solution after 28 days of exposure and a relative compressive strength compared to 28-day compressive strength in ambient environment corresponding to the mixing design. The results of this experiment are as presented in Table 8.
Furthermore, the results are there in chart 3 which shows characterization of compressive strength values in normal and acidic environments

The placement of this type of concrete in the acidic environment has been accompanied by a slight decrease in compressive strength, which varies based on the mixing scheme and the amount of alternative wollastonite powder explained by the influence of sulfuric acid of sample and reaction with cement paste and stone materials caused to corrode and lower resistance.

4. Conclusions

Based on the findings of this study, the following results can be drawn:

1. The use of wollastonite powder to manufacture the conventional concrete with a good compressive strength, in addition to improving some of the properties of the concrete, has protected the environment and has caused the material to be naturally recycled.
2. By increasing the amount of wollastonite and maintaining the recycled aggregate in concrete, the compressive strength and tensile strength of the concrete has been slightly decreased.
3. By raising the wollastonite percentage, the concrete resistance to the acidic environment has been decreased, which is less than 10% for 40% replacement of this material with cement.
4. The results of the Brazilian test have shown a significant increment in tensile strength in samples containing 30 and 40% wollastonite powder.
5. A study of weight variations of samples containing wollastonite powder has shown a moderately acidic environment but no significant weight loss.
6. Compressive strength of the designs studied in this research has indicated that by using micro silicon powder, it is possible to use the mineral wollastonite to half the cement weight in concrete.

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