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ORIGINAL RESEARCH

Combined Porcelain Ceramic and Recycled Concrete Aggregates Used as Replacement for Coarse Aggregates in Concrete

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Abstract

The increasing production of construction waste on the one hand and the use of concrete as a widely used material in the construction industry, on the other hand, has always led researchers to reuse construction waste in concrete. Among the recycled materials that can be used in concrete, we can mention porcelain ceramic and recycled concrete. In the present study, these two types of recycled aggregates (recycled porcelain ceramics and recycled concrete) alone and together in different percentages of 20%, 40%, and 60% are used as the replacement of coarse aggregates in concrete with a strength of more than 50 MPa and high flowability. Slump test, compressive and flexural strength, water absorption, and water penetration tests have been performed on 150 samples made in 10 mixing designs along with an SEM test. The results showed that all the mixing designs had slumps of more than 180 mm. The compressive strength of the control sample averaged 60 MPa and the samples containing recycled aggregates averaged 68 MPa. Also, by combining two types of recycled aggregates, both the 7-day and 28-day strength increased with increasing replacement percentage with a linear trend. The highest increase was 28% for porcelain aggregates and 17% for combined recycled aggregates. In addition, the water penetration rate in the samples containing the combined recycled aggregates showed a significant decrease compared to the control sample. In the SEM test, it was observed that the samples containing the combined aggregates had a thicker and denser matrix.

Keyword:
Recycled Concrete, Porcelain Ceramic, Compressive Strength, High Strength Concrete.

1. Introduction

The construction wastes are constantly increasing across the world due to the expansion of construction and the replacement of aged buildings with new ones. These wastes include wood, glass, plastics, stone, brick pieces, concrete, and ceramic. Millions of tons of waste are generated every year in each country. Recycling is a solution to mitigate the environmental impacts of accumulated wastes and has been of great interest to researchers in recent decades. The replacement of aggregates and cement with recycled materials in concrete production has become a core of attention as it reduces environmental depletion. There is a significant body of research on the production of eco-friendly concrete. Concrete is used in large quantities in the construction industry, and it would be efficient to exploit waste in concrete production (Xiao et al. 2012; Kou et al. 2008; Okechi et al. 2022; Pacheco-Torgal and Ding 2013; Mostofinejad et al. 2017). In particular, some recycled wastes can provide pozzolanic or quasi-pozzolanic properties in concrete and improve its mechanical properties and durability (Rostami et al. 2020; Hendi et al. 2020; Hendi et al. 2018; Pellegrino and Faleschini 2016; Evangelista and Guedes 2019). For instance, recycled glass particles of different sizes can partially replace cement or fine/coarse aggregates in the production of concrete. Research has shown that the replacement of common aggregates with glass particles would not significantly reduce concrete strength, and the replacement of fine aggregates with recycled glass powder improves strength and durability in light of its

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quasi-pozzolanic properties (Hendi et al. 2017; Mostofinejad et al. 2020).

Furthermore, alabaster and granite waste improves the microstructure and strength of concrete (Vijayalakshmi et al. 2013). Insulators in power towers have also been used as recycled aggregates in concrete and have been able to improve properties such as concrete strength (Gharibi et al. 2022). Several studies utilized rice husk ash (RHA) to partially replace cement in concrete (RawaidKhan et al. 2012).

Concrete waste accounts for a large portion of construction waste. It arises from the disposal of extra concrete in construction or the destruction of the existing concrete structures. Numerous studies have been conducted on the use of recycled concrete to replace aggregates in concrete production (Gharibi et al. 2022).

The literature on the use of recycled concrete as aggregates reported a reduction in concrete performance, an increase in permeability, and a decrease in strength. Earlier work also reported several transition zones, including the recycled concrete composite, recycled concrete-cement paste interface, and cement paste-common aggregate interface, as determinants of mechanical behavior and durability in concrete (Li et al. 2021; Etxeberria Larrañaga 2004; Tavakoli et al. 2018; Lauritzen 2004; Ahmed and Lim 2021).

Recycled porcelain has also been of interest to researchers in recent decades. However, several studies employed conventional ceramic to replace the aggregates in concrete. Porcelain has a high content of SiO_2, and it is produced at approximately 900°C, therefore, porcelain has very low water absorption and high strength. Furthermore, porcelain waste particles have sharp edges and undergo strong contact with cement paste, which potentially enhances the strength of concrete (Silvestre et al. 2013; Ghos et al. 2016; Piyaphanuwat and Asavapisit 2017; Zimbili et al. 2014; Gaikwad and Bhonde 2019).

Floor, roof tile, and ceramic brick waste with fine particles could serve as pozzolanic materials. Research has shown that the mixture of SiO_2 in ceramic waste and $Ca(OH)_2$ may induce pozzolanic and secondary hydration (C-S-H), enhancing concrete durability and strength (Higashiyama et al. 2013; Keshavarz and Mostofinejad 2019).

Several studies have indicated that porcelain waste and even polished porcelain increased compressive and flexural strengths and thermal resistance in concrete. Water absorption was reported to be higher in most recycled concretes than the conventional ones; however, the increased water absorption level was acceptable (Talei and Mostofinejad 2021; Al-Luhybi 2017; Sampaio et al. 2017; Jasim et al. 2019; Jasim et al. 2021; El-Abidi et al.2022; Wang et al. 2021; Guerra et al. 2009; Ray et al. 2021; Keshavarz and Mostofinejad 2020; Jamal et al. 2018).

The present study evaluates the simultaneous use of recycled concrete aggregates and porcelain waste. Porcelain and recycled concrete each replace coarse aggregates at 20%, 40%, or 60% fractions. Then, a combination of recycled concrete and porcelain with a 1:1 ratio is employed to replace standard coarse aggregates. The compressive test (curing ages of 7 and 28 days), flexural test, water penetration test, water absorption test, and Scanning Electron Microscopy (SEM) are carried out.

2. Experimental setup

A total of 10 mixed designs are defined and named, as shown in Table 1.

Table 1: Mix designs and descriptions

Mix design No.	Description
1	Control sample
2	Replacement of 20% of gravel with porcelain ceramic chips
3	Replacement of 40% of gravel with porcelain ceramic chips
4	Replacement of 60% of gravel with porcelain ceramic chips
5	Replacement of 20% of gravel with recycled concrete
6	Replacement of 40% of gravel with recycled concrete
7	Replacement of 60% of gravel with recycled concrete
8	Replacement of 20% of gravel with ceramic and recycled concrete aggregates (10% of each)
9	Replacement of 40% of gravel with ceramic and recycled concrete aggregates (20% of each)
10	Replacement of 60% of gravel with ceramic and recycled concrete aggregates (30% of each)

The control mix design was defined based on ACI211-14 (ACI 2014). To produce recycled concrete aggregates, standard cubic concrete specimens were collected from concrete test laboratories. The compressive strength of these specimens was mostly higher than 20 MPa since they were structural concretes used in ordinary urban buildings. They had an age of much longer than 28 days. They could be assumed to be a concrete waste.

To produce porcelain grains, unglazed ceramic was prepared. Then, both concrete waste and porcelain were crushed using a crusher. Regular gravel, recycled concrete, and ceramic waste were graded based on the provisions of ASTM C136 (ASTM 2014), as shown in Figs. 1-7. According to Fig. 3, recycled ceramic had higher fineness than the standard level. This arose from the higher power of the crusher; in fact, ceramic grains mostly served as fillers.

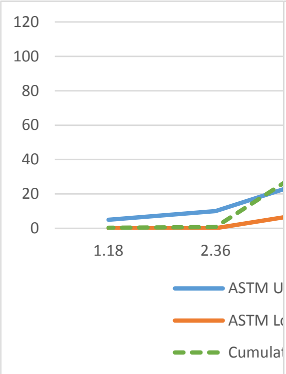

Fig. 1: Grading curve for gravel aggregates

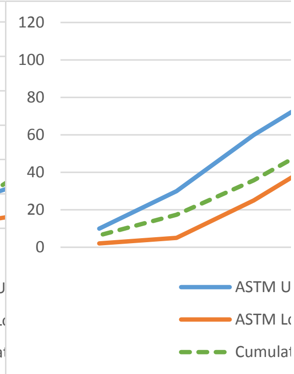

Fig. 2: Grading curve for sand

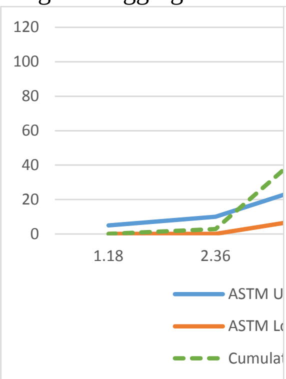

Fig. 3: Grading curve for ceramic aggregates

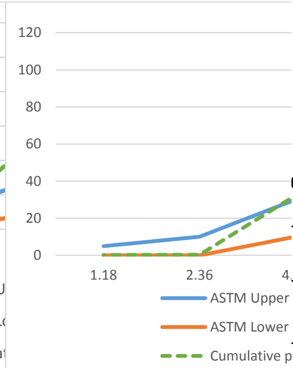

Fig. 4: Grading curve for recycled concrete aggregates

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(a) (b)

Figure 7. Conventional aggregates; (a): Sand, (b): Gravel

...es of Portland cement type II, the product of the Ardestan cement factory

			MgO	SO_3	SiO_2	LoI	C_3A%	I.R
			1.9±0.2	*1.5±0.2*	*22±0.4*	*1±0.2*	*6.5±1*	*0.46±0.2*
(ISIRI 2020)	*6≥*	*6≥*	*5≥*	*3≥*	*≥20*	*3≥*	*8≥*	*0.75≥*
ASTM C150 (ASTM 2012)	*6≥*	*6≥*	*6≥*	*3≥*	--	*3≥*	*8≥*	*1.5≥*

Type II Portland cement from the Ardestan Cement Factory, Iran, was employed. Tables 2 and 3 report the physical and chemical characteristics of the cement (manufacturer's data) in compliance with the Iranian Standard for Portland Cement ISIRI-389 (ISIRI 2020) and ASTM C150 (ASTM 2012).

Figure 5. Recycled concrete aggregates

Figure 6. Recycled porcelain ceramic aggregates

Table 3. Physical properties of Portland cement type II, the product of Ardestan cement factory

	fineness modulus (cm^2/gr)	Setting time (min)		Standard expansion test of cement by autoclave method (%)	Compressive strength (MPa)		
		Initial	final		3 days	7 days	28 days
Cement used	۳۰۰۰±۵۰	۹۵±۵	۱۵۰±۱۰	۰/۱۴±۰/۱	≥۱۶/۶	≥۲۶/۹	≥۳۶/۲
ISIRI-389 (ISIRI 2020)	≥۲۸۰۰	≥۴۵	۳۶۰≥	۰/۸≥	≥۱۱/۷	≥۱۹/۶	≥۳۱/۸
ASTM C150 (ASTM 2012)	≥۲۸۰۰	≥۴۵	۳۷۵≥	۰/۸≥	≥۱۰	≥۱۷	≥۲۷/۹

Micro-silica was obtained from Iran Ferrosilice Company, as reported in Table 4.

Table 4: Properties of used micro silica

Colure	Particles size	Special weight	Special surface (m^2/gr)	Bulk Density (kg/m^3)
Light gray	µm**40**>	2.2	15-30	310-350

Table 5 describes the polycarboxylate ether superplasticizer.

Table 5: Properties of superplasticizer

PH	6.5
Appearance	Clear liquid
Volumetric mass	1.05 kg/Litre @ 20℃
Freezing point	-4℃
Alkaline content	Less than 1.5 gram/liter Na_2o

Once the recycled concrete and porcelain had been crushed, the water absorption test was carried out based on ASTM C566-89 (ASTM 2004) and ASTM C127-88 (ASTM 2015). It was found that recycled porcelain and concrete had a water absorption rate of 1% and 5.38%, respectively.

Table 6 provides the characteristics of recycled porcelain and concrete aggregates.

Table 6: Properties of gravel, sand, and porcelain aggregates

Aggregate	Density (G_A)	Water absorption in standard surface dry mode ($W_{ssd, A}$)	Dry-rod bulk density (g)	Fineness modulus (FM)
Gravel	2650	0.05	1590	-
Sand	2650	0.08	-	3.409
Porcelain Ceramic Aggregates	2450	0.07	s-	-

According to Figs. 1-7, the aggregates were constrained to a maximum nominal size of 12.5 mm to enhance concrete strength by increasing the specific surface area of aggregates and, as a result, hydrated cement paste (HCP) as the transition zone.

As mentioned, the control mix design was defined based on ACI 211, with nine mix designs containing replaced aggregates. Table 7 provides the ten mixed designs. The present work replaced common aggregates once with recycled porcelain aggregates at different fractions, once with recycled concrete aggregates at different fractions, and once with a combination of recycled concrete and porcelain aggregates. The control mix design had a slump of higher than 150 mm and a characteristic compressive strength higher than 50 MPa. It is noted that C., SF., W., G., P.A., C.A., and SP denote the am of the cement, micro-silica, water, sand, porcelain aggregates, recycled concrete aggregates, and superplasticizer, respectively.

Table 7: Mix Designs of Samples

Mix No.	Weight of concrete components (kg/m^3)							
	C.	Sf.	W.	S.	G.	P.A.	C.A.	SP.
1	423	47	188	1100	670	0	0	3.3
2	423	47	188	1100	536	67	0	3.8
3	423	47	188	1100	402	134	0	4.2
4	423	47	188	1100	268	201	0	4.4
5	423	47	188	1100	536	0	67	3.8
6	423	47	188	1100	402	0	134	4.3
7	423	47	188	1100	268	0	201	4.5
8	423	47	188	1100	536	33.5	33.5	3.7
9	423	47	188	1100	402	67	67	3.8
10	423	47	188	1100	268	100.5	100.5	4.5

2.1 Specimens

This study performed the slump test, compressive test (on 100-mm cubic specimens, three at the age of 7 days and three at 28 days), and three-point flexural test on 100*100*400mm prismatic specimens with a support spacing of 300 mm at the curing age of 28 days (three specimens of each mix design), water absorption test, and 72-hour water penetration test on 100mm cubic specimens (three specimens of each mix design at the age of 28 days). Hence, a total of 120 cubic specimens and 30 prismatic specimens were produced and cured in water at ambient temperature for 28 days.

3. Results

3.1. Slump test

Table 8 provides the fresh concrete slump test results of all ten mix designs based on the provisions of ASTM-C143-78 (ASTM 1979). As shown, the specimens were found to have slumps larger than 180 mm. This is a remarkable result as earlier work reported reduced slumps upon the use of ceramic waste and even concrete waste. In particular, considering the sharp edges of porcelain aggregates and the water absorption of recycled concrete aggregates, such slump levels represent self-compacting concretes with high performance, and satisfactory water penetration, water absorption, and compressive strength.

Table 8: Slump test results

Mix	1	2	3	4	5	6	7	8	9	10

No.										
Slump (mm)	185	185	180	185	185	180	180	185	185	180

3.2. Compressive strength

Table 9 reports the compressive strengths of the specimens at the ages of 7 and 28 days. The compressive test was carried out based on BS EN 12390 (BS EN 2002). The stress values were obtained by dividing the load on the surface area of the 100*100 mm cubic specimens. Fig. 8 plots compressive strength versus recycled waste fraction. The average 28-day compressive strength of each mix design is reported. Since the cubic specimens had a size of 100*100 mm, two factors were used to convert the cubic strength into the strength of standard cubic specimens, and then, into the standard compressive strength (for cylindrical specimens). It should be noted that the product of these two factors is 0.75. Therefore, the standard compressive strengths reported in the plots are smaller than the tested strengths.

Table 9: Compressive test results

Mix No.	7-day compressive strength (MPa)			28-day compressive strength (MPa)		
	1st sample	2nd sample	3rd sample	1st sample	2nd sample	3rd sample
1	43	42	44.1	59.5	61.8	60.6
2	43.8	44.7	43.8	65.2	65.1	64.3
3	44.1	45.8	45.7	68.9	69.3	65.8
4	50.9	49.9	51.1	78.1	77.9	76.8
5	46.1	45.8	46.6	62.9	63.1	63.2
6	46.5	46.9	47.3	66.1	65.8	65.6
7	52.8	54.7	53.9	68.9	68.7	68.4
8	43.2	42.8	43.2	64.9	66.1	65.1
9	45.1	43.9	43.9	67.6	68.1	67.6
10	49.2	49.4	50.8	72.3	71.3	70.3

Fig. 9 compares the concrete specimens to the control specimen in the 28-day compressive strength.

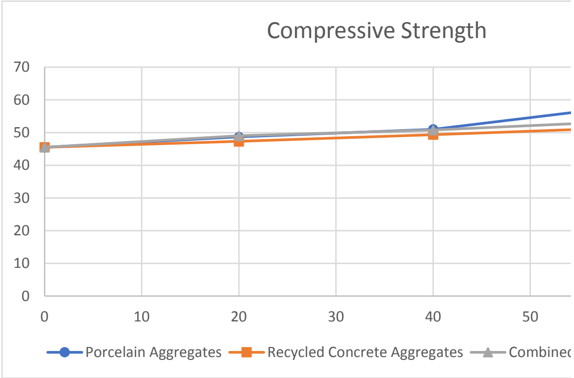


Fig. 8: Compressive strength changes of samples in terms of the aggregate replacement percentage

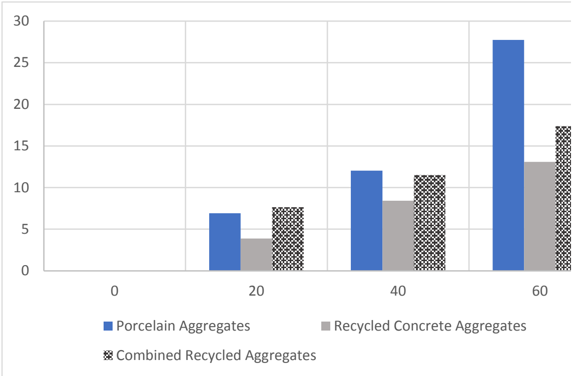


Fig. 9: Increase of compressive strength compared to the control sample (%), depending on the type of recycled aggregate and the percentage of replacement

According to Fig. 9, the replacement of standard aggregates with recycled porcelain or concrete aggregates increased compressive strength at all three fractions. A rise in the recycled waste fraction increased compressive strength compared to the control specimen. According to Fig. 10, individual recycled porcelain aggregates led to the highest compressive strength, while the hybrid waste aggregates had the second-highest contribution to the compressive strength. The individual recycled concrete aggregates had the lowest impact on the compressive strength enhancement of the concrete.
Fig. 10 represents compressive strength enhancement upon the use of the three types of recycled waste aggregates at different fractions along with the regression coefficient of R^2 for the fitted curve. As indicated, the compressive strength showed almost linear behavior under all three types of recycled waste aggregates. These lines are formulated below.

Porcelain Recycled Aggregates	IP=0.44*RP-1.58
concrete Recycled Aggregates	IP=0.22*RP-0.22
Combined Recycled aggregates	IP=0.28*RP+0.73

ease Percentage

Replacement Percentage

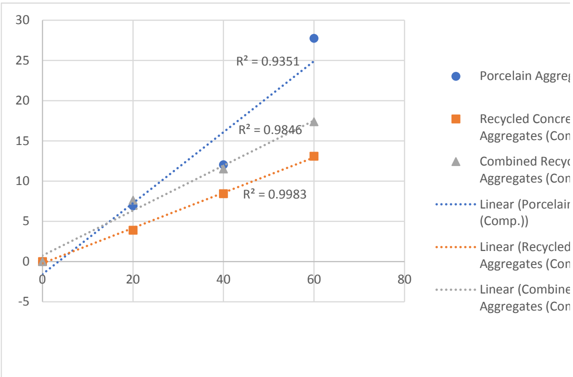


Fig. 10: Increase in compressive strength (%) trend lines

Recycled porcelain aggregates increased compressive strength by 7%, 12%, and 28% at fractions of 20%, 40%, and 60%, respectively. Furthermore, recycled concrete aggregates at fractions of 20%, 40%, and 60% led to a 4%, 8%, and 13% rise in compressive strength, respectively. The hybrid recycled waste aggregates enhanced compressive strength by 8%, 12%, and 17% at fractions of 20%, 40%, and 60%, respectively. Fig. 11 compares the recycled aggregate-containing concretes to the control specimen in strength at different waste fractions at the age of 7 days. As illustrated, the 7-day strength of the waste aggregate concretes was higher than that of the control specimen, and a rise in the waste fraction raised the 7-day strength.

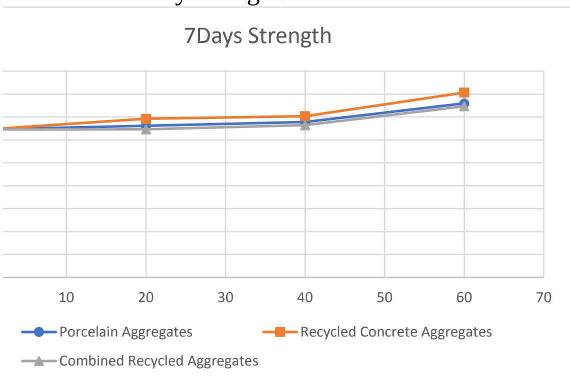


Fig. 11: 7-Day compressive strength changes of samples in terms of the aggregate replacement percentage

To further evaluate strength enhancement upon the replacement of standard aggregates with waste aggregates at the ages of 7-28 days, figs. 12-14 plot compressive strength versus waste fraction. As can be seen, porcelain aggregates at fractions of 20%, 40%, and 60% led to 2.5%, 5.0%, and 17.5% higher strength at the curing age of 7 days and 7%, 12%, and 28% higher strength at the age of 28 days, respectively. Thus, it can be said that recycled porcelain aggregates had even a greater contribution to strength enhancement at longer ages.

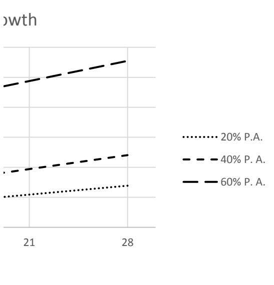


Fig. 12: Strength growth of concrete containing porcelain aggregates

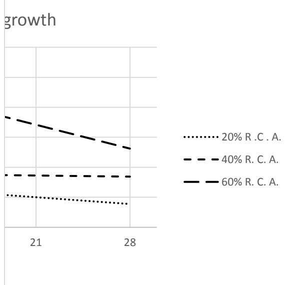


Fig. 13: Strength growth of concrete containing recycled concrete aggregates

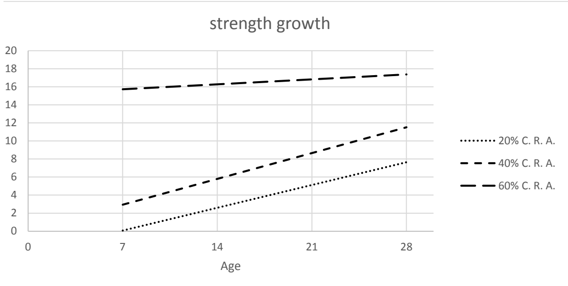


Fig. 14: Strength growth of concrete containing combined recycled aggregates

Table 10: Strength increase percentage of samples to control case

	Replacement aggregates	Replacement percentage		
		20%	40%	60%
Increase of 28 days strength to control mix (%)	P. A.	۷	۱۲	۲۸
	R. C. A.	۴	۸	۱۳
	C. R. A.	۸	۱۲	۱۷
Increase of 7 days strength to control mix (%)	P. A.	۳	۵	۱۸
	R. C. A.	۷	۹	۲۵
	C. R. A.	۰	۳	۱۶

* P.A.: Porcelains Aggregates;
* R. C. A.: Recycled Concrete Aggregates;
* C. R. A.: Combined Recycled Aggregates.

Recycled concrete aggregates at fractions of 20%, 40%, and 60% raised the compressive strength by 7%, 9%, and 25% at the age of 7 days and by 4%, 8%, and 13% at the age of 28 days, respectively. This implies that recycled concrete aggregates had a lower contribution than porcelain aggregates to compressive strength at the ages of 7-28 days. This may be attributed to the sharp edges of porcelain aggregates.

The concretes with hybrid waste aggregates increased in compressive strength compared to the control specimen over time. Hybrid aggregates increased compressive strength by nearly 0%, 3%, and 16% at the age of 7 days and by 8%, 12%, and 17% at the age of 28 days under fractions of 20%, 40%, and 60%, respectively.

Porcelain aggregates led to an average rise of 140% in compressive strength (i.e., 2.4-fold strength). Recycled concrete aggregates raised compressive strength by 70% on average, and hybrid waste aggregates led to an average compressive strength nearly 4.4 times as high as the control specimen. Interestingly, a rise in the waste fraction reduced the strength enhancement rate at the ages of 7-28 days. This suggests that the transition zone formed more effectively at lower waste fractions. In other words, new transition zones (between the recycled waste aggregates and cement paste and between cement paste and standard aggregates) at high waste fractions diminished compressive strength enhancement.

Table 10 reports compressive strengths at different waste aggregate fractions. Porcelain, recycled concrete, and hybrid aggregates led to an average rise of 8.6%, 13.6%, and 6.3% in the 7-day compressive strength and 15.6%, 8.3%, and 12.3% in the 28-day compressive strength, respectively. The hybrid of recycled porcelain and concrete aggregates led to lower 7-day compressive strength than individual recycled porcelain and recycled concrete aggregates; however, at the age of 28 days, the hybrid aggregates resulted in higher compressive strength than individual recycled concrete aggregates and lower compressive strength than individual porcelain aggregates. It should be noted that the concretes with all three types of recycled waste aggregates had higher compressive strength than the control specimen.

3.3. Flexural strength

Table 11 shows the flexural strengths of the concretes. The fracture load of the flexural specimens in the three-point flexural test under ASTM C78-09 (ASTM 2010) and flexural strengths (rupture modulus) are provided. Figs. 15 and 16 plot flexural strength and flexural strength enhancement versus waste aggregate fraction. As can be seen, the average flexural strength of the waste aggregate concretes was lower than that of the control specimen. Porcelain, recycled concrete, and hybrid aggregates led to an average reduction of approximately 11%, 7%, and 12% in flexural strength, respectively.

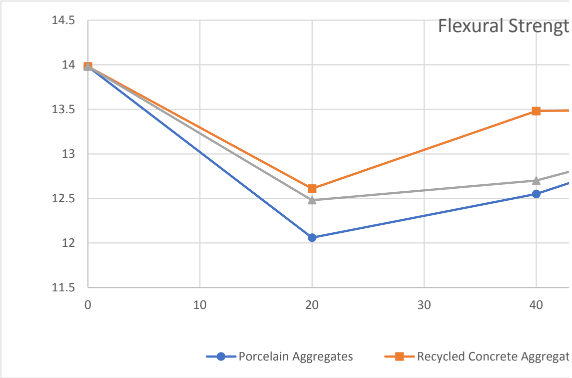


Figure 15. Flexural strength changes according to aggregate replacement percentage

Table 11. Failure loads in flexure test (kN)

Mix No.	1st sample	2nd sample	3rd sample	Average flexural strength (MPa)
1	29.76	32.16	31.29	13.98
2	26.60	27.41	26.40	12.06
3	28.80	26.45	28.39	12.55
4	28.32	31.36	29.54	13.38
5	26.52	29.41	28.16	12.61
6	29.69	30.20	30.00	13.48
7	29.47	30.27	30.37	13.52
8	26.65	28.68	27.90	12.48
9	28.42	28.30	27.81	12.7
10	26.93	31.72	30.50	13.37

According to Table 11 and Fig. 16, the replacement of standard aggregates with recycled waste aggregates reduced flexural strength. The flexural strength reduction was smaller at larger waste fractions; the lowest reduction in flexural strength occurred at a waste fraction of 60%. Recycled concrete and porcelain aggregates resulted in the lowest and highest reductions in flexural strength, respectively. It is worth mentioning that recycled concrete aggregates at a fraction of 60% decreased flexural strength by 3.5% on average, which shows a negligible decrease.

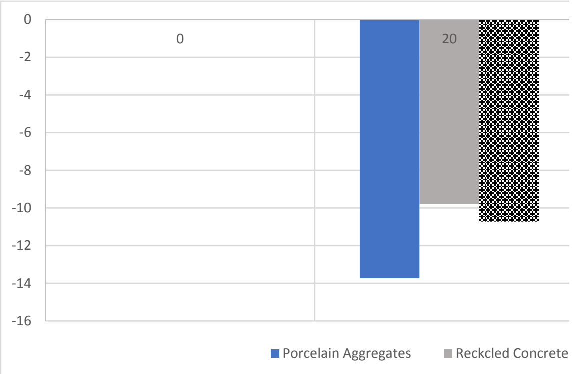


Fig .16 change of flexural strength in different percentage of aggregates replacement

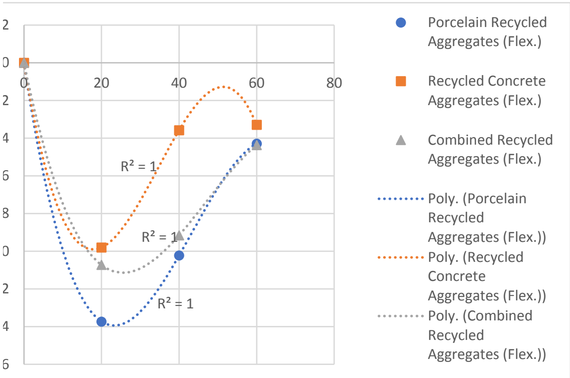
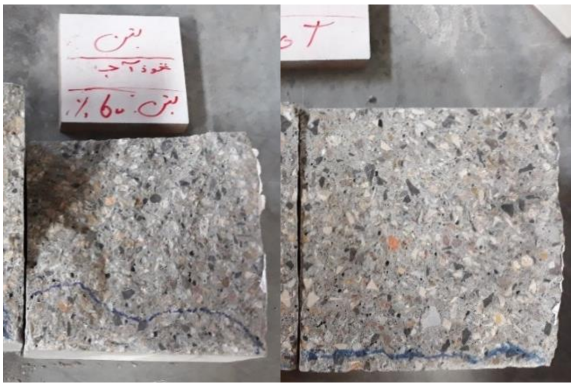


Fig. 17 Fitted curve on changes in flexural strength to replacement percentage



(a) (b)

Fig. 18

A rise in the porcelain fraction reduced water penetration, except at the fraction of 20% –the bar charts of the water penetration difference from the control specimen in Fig. 20, however, the average penetration depth was found to be nearly 14 mm (10% higher than the control specimen).

d Aggregates	IP = -0.0003*RP^3 + 0.0401*RP^2 - 1.3644*RP
Aggregates	IP = -0.0005*RP^3 + 0.0475*RP^2 - 1.2566*RP
ed aggregates	IP = -0.0002*RP^3 + 0.0267*RP^2 - 0

ease Percentage

Replacement Percentage

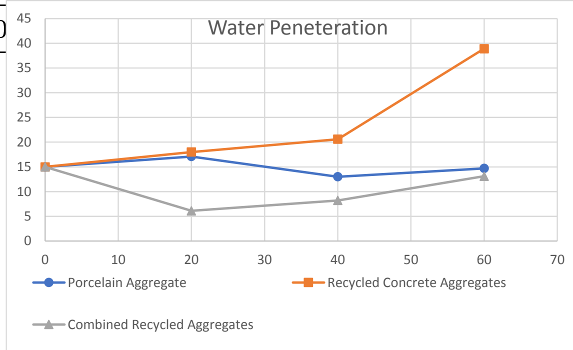


Fig. 19 water penetration changes according to replacement percentages

Fig. 17 plots the third-order fitted curves of the flexural strength difference between the recycled aggregate concretes and control specimen with an R^2-value of 1. The fitted curves are formulated below.

3.4. Water penetration

The water penetration test was carried out on the mix designs under the BS EN-12390-8 (BS EN 2019). The specimens were subjected to a water pressure of 5 bars and were split into halves. The water penetration depths in both halves were measured using a caliper. Fig. 18 shows a specimen split into halves with the water penetration lines. The larger penetration depth would be reported as the penetration value. Table 12 reports the average water penetration depth of three specimens of each mix design. Fig. 19 plots the average water penetration depth of the halves versus waste fraction.

Table 12: Water penetration (mm)

Mix No.	1st part	2nd part
1	11.0	15.0
2	12.0	17.1
3	13.0	13.0
4	14.7	13.6
5	18.0	16.5
6	20.6	13.4
7	38.9	34.4
8	5.5	6.1
9	5.9	8.2
10	11.6	13.1

The concrete with recycled concrete aggregates showed 32%, 31%, and 189% higher water penetration than the control specimen. This indicates that recycled concrete aggregates increased water penetration into the concrete, with a direct relationship between the waste fraction and water penetration.

Interestingly, hybrid waste aggregates reduced water penetration into the concrete. The water penetration depth was 55% and 5% lower than that of the control specimen at the hybrid waste fractions of 20% and 60%, respectively. In other words, the concretes that contained hybrid waste aggregates had lower water penetration than the control concrete, and a rise in the fraction lowered the water penetration depth reduction rate.

Fig. 20 plots quadratic curves fitted to the penetration depths of the concretes containing waste aggregates, along with the R^2-values. The R^2-value of 1 represents a high fit. As can be seen, a rise in the recycled concrete aggregate fraction raised water penetration, while the concretes containing porcelain or hybrid waste showed lower water penetration at higher aggregate fractions.

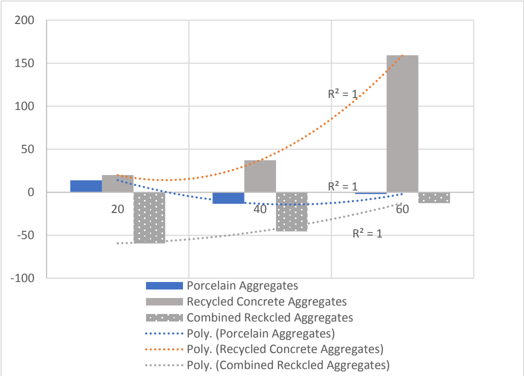


Fig. 20 Fitted curves on water penetration changes to control specimen

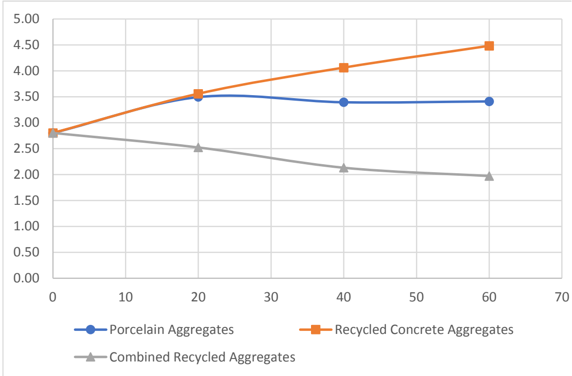


Fig. 21 water absorption changes according to replacement percentages

3.5. Water absorption

The water absorption test was implemented on the concrete specimens under ASTM C642 (ASTM 2013). The specimens at the age of 28 days were kept within water for 24 h. The wetted specimens were weighed. Then, the specimens were placed within a furnace to be completely dried at 110°C and reweighed. The difference between the wet and dry weights was divided by the dry weight to obtain water absorption, as shown in Table 13.

Table 13: Water absorption (%)

Mix No.	1st sample	2nd sample	3rd sample
1	2.80	2.90	2.70
2	3.48	3.51	3.49
3	3.41	3.37	3.40
4	3.51	3.34	3.38
5	3.67	3.47	3.53
6	4.10	4.20	3.89
7	4.89	4.28	4.30
8	2.61	2.47	2.51
9	2.01	2.18	2.20
10	2.05	1.85	2.01

Figs. 21 and 22 depict the average changes in the water absorption of the concretes at different waste fractions and the average water absorption ratio of the concretes to the control specimen. Fig. 3333 shows the fitted water absorption curves of the concretes containing recycled concrete, porcelain, and hybrid waste aggregates, along with the R^2-values. As can be seen, the water absorption difference from the control specimen had an almost direct relationship with the waste fraction. It can be said that:

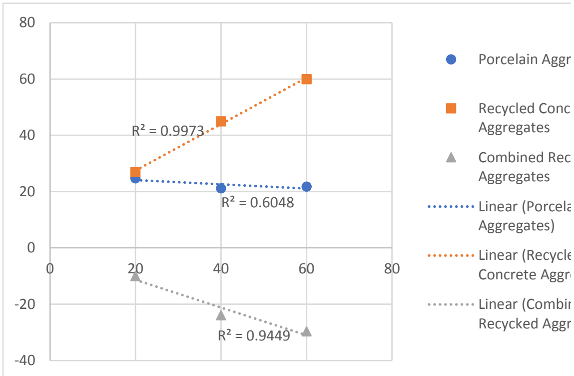


Fig. 22 Fitted curves on water absorption changes to control specimen

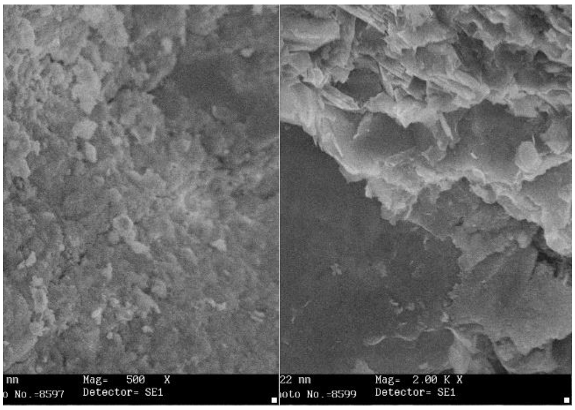
(I) Porcelain aggregates at a fraction of 20% increased water absorption by nearly 25% compared to the control specimen. A further rise in the porcelain fraction led to smaller changes in water absorption, and absorption remained almost unchanged at larger fractions.

(II) An increase in the recycled concrete aggregate fraction from 20% to 60% raised water absorption from 27% to 60%.

(III) Hybrid waste aggregates diminished water absorption by 10-30%.

3.6. Scanning electronic microscope (SEM)

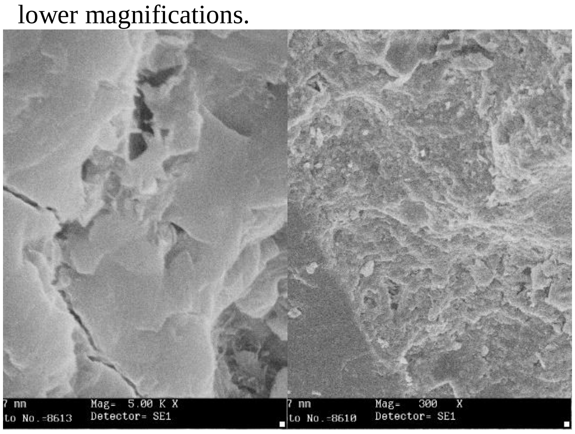
The specimens were subjected to SEM to evaluate their microstructures (Keshavarz and Mostofinejad 2020). Here, only the SEM results of the specimens with 60% waste aggregates are provided. Figs. 23-26 depicts the SEM images of the control specimen and the concretes containing 60% recycled concrete, recycled porcelain, and hybrid aggregates.



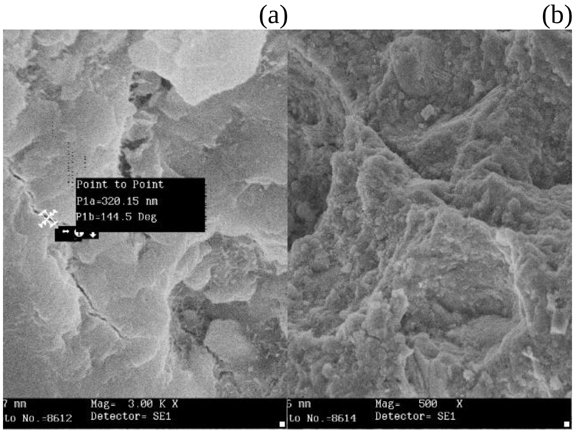
(a) (b)

Fig. 23: Control specimens

The interfacial transition zone between the recycled concrete aggregates and cement mortar is observable in the SEM image of the specimen with 60% recycled concrete aggregates at a 50X magnification, which is presented in fig. 24. Vacancies are even observable at lower magnifications.



(a) (b)



(c) (d)

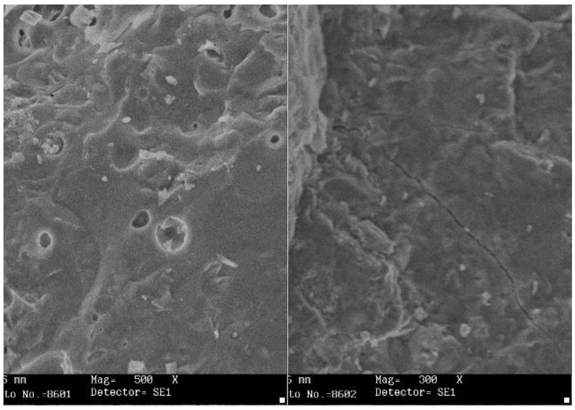
Fig. 24: 60% concrete

Vacancies and the interfacial transition zone between recycled porcelain and cement mortar are observed in the SEM image of the concrete with 60% porcelain at a 500 times magnification (Fig. 25).

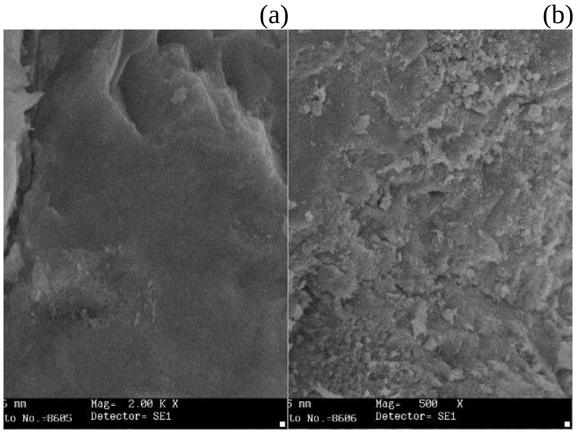
For the specimen with 60% hybrid aggregates (i.e., 30% recycled concrete and 30% porcelain), a more solid and compact matrix appeared, as shown in Fig. 26. At magnifications of 2000X and 5000X, interfacial transition zones are observed between the recycled aggregates and cement paste.

4. Conclusion

In the present study, ten mix designs were produced, including a control concrete and nine concretes in which standard aggregates were partially replaced with recycled concrete, porcelain, or hybrid recycled concrete-porcelain aggregates. The experimental setup included the slump test, compressive test, flexural test, water penetration test, water absorption test, and SEM. The results can be summarized as:

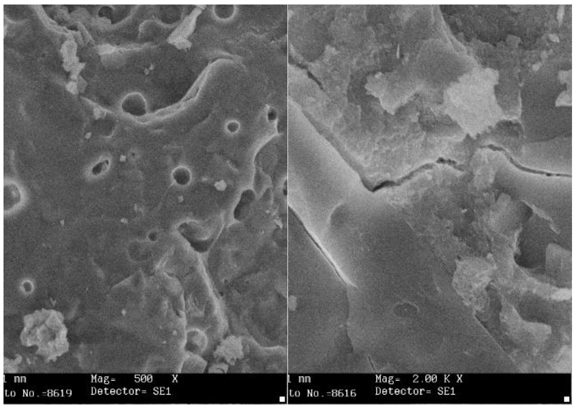


(a) (b)

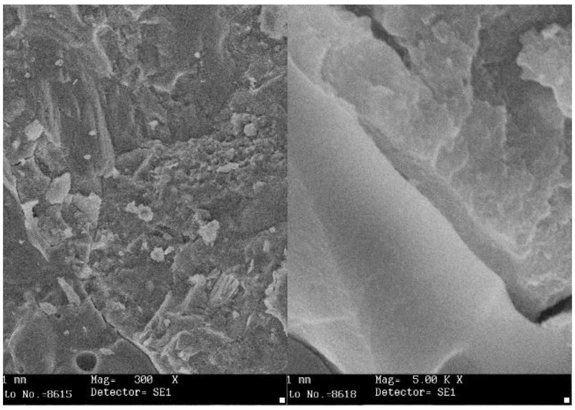


(c) (d)

Fig. 25: 60% Porcelain



(a) (b)



(c) (d)

Fig. 26: 60% combined

(1) The specimens had slumps larger than 180 mm. Hence, the concretes containing all three types of recycled aggregates were concluded to have high consistency.
(2) The average compressive strength of the control specimen was 60 MPa, while that of the recycled aggregate concretes was found to be 68 MPa. The flexural strengths of the control and recycled aggregate concrete were obtained to be nearly 14 and 13 MPa. Therefore, they could be viewed as relatively high-strength concretes.
(3) An increase in the fraction of all three types of recycled aggregates increased compressive strength at both curing ages of 7 and 28 days. The largest and smallest compressive strength enhancements occurred under recycled porcelain and hybrid aggregates, respectively. Porcelain aggregates led to a maximum increase of 28% in compressive strength, whereas hybrid aggregates enhanced compressive strength by a maximum of 17%.
(4) The relationship between the 28-day compressive strength and waste fraction was efficiently fitted to a curve. Porcelain and hybrid aggregates led to a maximum rise of 28% and 17% in compressive strength, respectively.
(5) Compressive strength underwent larger growth rates at larger porcelain fractions, while it showed smaller growth rates at larger recycled concrete aggregates. Hybrid aggregates led to a positive growth rate of compressive strength at higher fractions at the ages of 7-28 days.
(6) Recycled aggregates reduced flexural strength compared to the control specimen. The largest flexural strength reduction was approximately 13%, while the smallest decrease in flexural strength was nearly 3%. An increase in the waste fraction raised flexural strength, diminishing the flexural strength difference from the control specimen.
(7) The recycled aggregate concretes showed higher water penetration than the control specimen. The water penetration depth became even larger at higher waste fractions. Water penetration decreased in comparison to the control specimen as the porcelain fraction increased; the water penetration difference from the control specimen became negligible at larger porcelain fractions. The concretes containing hybrid aggregates showed substantial water penetration declines compared to the control specimen, regardless of the hybrid waste fraction; however, the water penetration decline became smaller as the hybrid waste fraction increased.
(8) Water absorption remained almost unchanged (nearly 20%) upon the replacement of standard aggregates with porcelain aggregates. However, the water absorption of the concretes containing recycled concrete aggregates linearly increased with the recycled concrete fraction. The concretes with hybrid aggregates showed lower water absorption than the control specimen, and a rise in the hybrid waste fraction linearly diminished water absorption.
(9) The microstructural analysis of the concretes via SEM revealed that the concrete containing recycled concrete aggregates had more vacancies. The transition zone between the recycled concrete aggregates and cement mortar was observable in the SEM image of the corresponding concrete, whereas the concrete containing hybrid aggregates showed a more solid and compact matrix.

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