Environment, Development and Sustainability (2022) 24:2685–2714
https://doi.org/10.1007/s10668-021-01551-5

Usage of recycled fine aggregates obtained from concretes with low w/c ratio in the production of masonry plaster and mortar

Gokhan Kaplan[1] · **Mesut Turkoglu**[2] · **Burak Bodur**[2] · **Oguzhan Yavuz Bayraktar**[2]

Received: 30 July 2020 / Accepted: 29 May 2021 / Published online: 4 June 2021
© The Author(s), under exclusive licence to Springer Nature B.V. 2021

Abstract

In this study, fresh and hardened aspects of mortars being produced from RFAs (recycled fine aggregates) obtained from concretes, w/c (water/cement) ratio of which varies in the range of 0.47–0.55 have been examined. On the mortars experiments such as those relating with workability, mechanical properties, drying shrinkage, sorptivity, and apparent porosity have been conducted. As flow diameters of mortars are kept at the value of 16 ± 2 cm, as a/c (aggregate/cement) ratio increased, w/c ratios of mortars also increased. As paste volume of mortars decreased, their mechanical properties got diminished. Increase in a/c ratio has impacted flexural strength negatively. In a mortar with a/c ratio of 5 and RFA ratio of %75, compressive strength of nearly 12 MPa has been obtained. As a/c ratio and compressive and flexural strengths of mortars increased, drying shrinkage values got reduced. Drying shrinkage value of mortars having a/c ratio of 7 and RFA ratio of %100 on 56th day has fallen below 1000 µm. By means of high grains below 75 µm within body of RFA, water penetration depth values of mortars have reduced. However, in mortars being produced by using RFA, attention should be paid to a/c ratio with regard to capillarity. Due to older cement paste situated on RFA surface, as RFA content increases, apparent porosity values of mortars have increased. As a conclusion, it has been determined that RFA will be used in production of mortar and plaster and it will be recycled and hence, sustainable building material could be obtained.

Keywords Sustainability · Recycled aggregate · Drying shrinkage · Capillarity · Workability

---

✉ Oguzhan Yavuz Bayraktar
obayraktar@kastamonu.edu.tr

[1] Faculty of Engineering, Department of Civil Engineering, Atatürk University, Erzurum, Turkey

[2] Faculty of Engineering and Architecture, Department of Civil Engineering, Kastamonu University, Kastamonu, Turkey

1 Introduction

Due to urbanization and rapid industrial growth, increasing amount of construction and urban transformation wastes and disposal of these wastes, has become a strategic subject in construction sector. The situation where these wastes cannot be disposed, creates serious ecological and environmental problems. For this reason, it has become important to intervene this situation by finding other solutions (Lee, 2009; Santha Kumar, 2019). By using urban transformation wastes in the construction sector instead of accumulating them in storage sites, can cause for contribution to be made with regard to waste management (Martín-Morales et al., 2011). Disposal of urban transformation wastes also makes significant amount of contribution for sustainable development (Geng & Sun, 2013). In each passing year, very big amount of construction and urban transformation wastes come out in the construction sector (Vieira et al., 2016). In European Union, 923 million tons of construction and urban transformation wastes have come out in year 2016 (Eurostat, 2018). Various studies have been realized in Europe in relation to recycling of these wastes and waste disposal with a rate of 90% could be achieved in year 2016 (Gloria M. Cuenca-Moyano et al., 2020; Eurostat, 2018). While World Bank anticipates that nearly 2.59 billion tons of construction and urban transformation wastes will come out until year 2030, it is predicted that this figure will reach to 3.40 billion tons until year 2050 (H. Guo et al., 2018; Kaza et al., 2018). It is known that total aggregate consumption in the world is quite high. Annual consumption of 37.400 mt in year 2010 has risen to nearly 50 billion mt in year 2019 (Rodrigues et al., 2013; Santha Kumar, 2019). Consumption of natural aggregates at such a high level creates big negativities on the surrounding ecosystems (de Brito & Saikia, 2013; Evangelista et al., 2015). The idea to produce concrete from RAs which are obtained from construction and urban transformation wastes has gained significant importance in the last 20 years (K. Zhang & Xiao, 2018). In recent times, lack of quality in aggregates and protection of natural resources have enabled for alternative usage of RAs. For this reason, usage of construction wastes as RA gets gradually widespread throughout the world. However, due to the reason that RA quality is low and quite variable, its being produced in concrete production has been seriously limited in many countries (Vivian W.Y. Tam et al., 2005; Xiao et al., 2012). As the usage of RAs reduces energy consumption besides enabling for protection of natural resources, it also reduces total construction costs (Olorunsogo & Padayachee, 2002). There are two basic reasons for using RA in concrete production. (Vivian W.Y. Tam et al., 2009). RAs that are obtained from construction and urban transformation wastes are used in concrete and mortar production both as fine and coarse aggregates, and hence, they contribute for sustainability (Santha Kumar, 2019).

RA (recycled aggregate) is obtained from construction and urban transformation wastes by means of breaking with the machines. For this reason, RA has a structure with sharp edges and old cement paste on its surface. There are cracks and pores on the old cement paste. Therefore, RAs have higher water retention capacity when compared with normal aggregate. For the concrete produced with RA, more amount of water is required for workability with respect to normal cement. This situation can cause for the new concrete being produced to be more porous. It has been stated that in the concretes being produced with RA, old cement paste situated between new cement paste and RA causes to weaken the interfacial transition zone (ITZ) (Etxeberria et al., 2007; Kou et al., 2012; Kwan et al., 2012; Padmini et al., 2009; Rahal, 2007). In some studies, it has been stated that water retention values of RFAs vary in the interval of 6–13% (Evangelista & de Brito, 2007; Fan et al., 2016).

Lopez has conducted workability tests for RFAs and he has stated that with the increasing RFA content, workability of mortars got reduced (Carro-López et al., 2015). Furthermore, due to water retention capacity, W/c impact ratio will be much lower than the normal mixture (Quattrone et al., 2016). When the morphology of RFA is examined, it is determined that the grains were angular and irregular (Evangelista et al., 2015; Geng & Sun, 2013). In the literature, there are studies revealing that RFA usage, mechanical properties, drying shrinkage, and strength of mortars and concretes are negatively impacted (Neno et al., 2014; Raeis Samiei et al., 2015; Zhao et al., 2015). These negative results obtained from the studies being conducted, was linked to the fact that RFA has a complex composition (Braga et al., 2012; Y. Guo et al., 2013; Kou & Poon, 2009; Sagoe-Crentsil et al., 2001). In the study conducted by Katz and Kulisch, it has been reported that RFA would be used in the mixtures with the appropriate w/c ratio. Besides, it was also stated that in case of RFA usage, setting periods were prolonged (Katz & Kulisch, 2017).

Usage of mortar and plaster bears importance in construction sector. For this reason, there is an increase in consumption of natural aggregate in each passing day. As it permits for usage of many types of standard cements in low ratios in the production of mortar, their strength levels can generally be low (< 10 MPa) (Martínez et al., 2018). In the literature, there are studies relating with RA usage in masonry mortars being used in structures (Fernández-Ledesma et al., 2016; Jiménez et al., 2013). RILEM has published various proposals in relation to RA usage in the production of new concrete (RILEM TC 121, 1994). Similar proposals are also specified in EN 206 standard (EN 206–1, 2000). In the literature, there are also studies relating with durability aspects of RAs. Rodrigues et al. stated that particles having size less than 0.063 mm contained harmful materials such as gypsum and clay and that due to this reason, in order for RFA to have good quality, it was required for these grains to be eliminated (Rodrigues et al., 2013). Lovato et al. stated that carbonation depth increased as being proportionate to the amount of RFA and size (Lovato et al., 2012). Evangelista and Brito obtained similar results in the study they conducted (Evangelista & de Brito, 2010). In the literature, there are other studies revealing that RFA usage has negative impact on durability (Kirthika & Singh, 2020; Pereira et al., 2012; Vieira et al., 2016). Even though it is mentioned about negative durability properties in cement-based composites with RA usage, there are many studies stating that RFA can be used in concrete production with an optimum ratio and a good curing (Geng & Sun, 2013; Salahuddin et al., 2020; Sim & Park, 2011; Zega & Di Maio, 2011).

In this study, fresh and hardened aspects of mortars being produced from RFAs obtained from concretes, w/c ratio of which varies in the range of 0.47–0.55 have been examined. Since the w/c ratio of masonry mortars is high, RFA's were obtained from old concretes produced with lower w/c. On the mortars experiments such as those relating with workability, mechanical properties, drying shrinkage, sorptivity, and apparent porosity have been conducted.

2 Materials

2.1 Cement

In the production of mortars, CEM I 42,5 R type of cement (Ordinary Portland Cement) in conformity with EN 197–1 standard has been used as binder. Chemical and physical properties relating with CEM I 42,5 R type of cement are given in Table 1.

Table 1 Chemical and physical properties relating with CEM I 42,5 R (OPC) type of cement

Oxide	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	LOI
(%)	64,08	19,03	4,15	3,56	1,04	3,01	0,45	0,71	3,55
Specific Gravity	3,13	Specific surface area (cm^2/g)			3230	Setting time (Initial/Final) (Min.)		210/270	

2.2 Aggregate

In the production of mortars, two different types of fine aggregates, namely river sand and recycled fine aggregate (RFA), have been used. Strength classes of concrete obtained from fine RAs are 25–35 MPa, and their w/c ratios are in the range of 0.47–0.55. Concrete strength classes have been selected by taking structure block constructed in Turkey as basis. In Fig. 1, aggregates used in experimental study are shown. In Fig. 2, sieve analysis results of RA and river sand are given.

Fineness module of river sand is 3.45 and fineness module of RA is 4.53. According to fineness module values, it is seen that RA has a structure with bigger grains. Specific gravity of river sand is 2.62 and specific gravity of RA is 2.53. Water adsorption values of river sand and RA are found to be 2.5% and 3.4%, respectively.

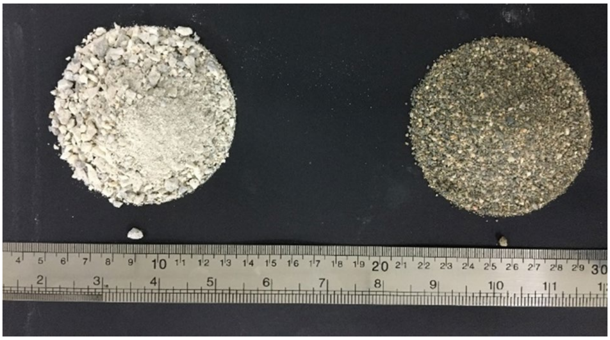


Fig. 1 General appearance of RFA and river sand

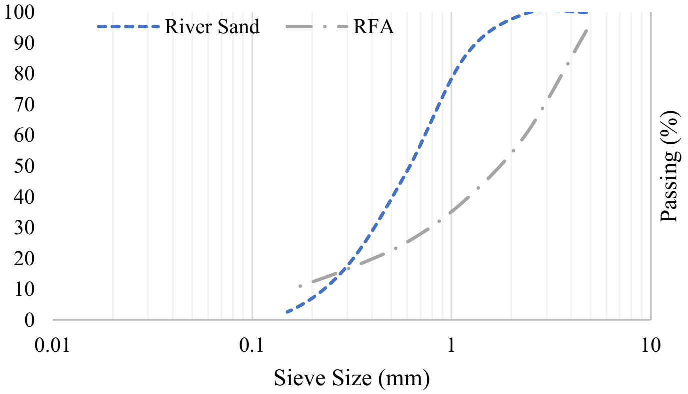


Fig. 2 Sieve analysis of aggregates

Table 2 Variables relating with mortar mixtures

	Level 1	Level 2	Level 3	Level 4	Level 5
RFA (%)	0	25	50	75	100
A/C	5	6	7		

Table 3 Mixture ratios and amounts relating with materials

Mix No	Mix ID	Mix Ratios			Material Quantities (g)			
		w/c*	RFA (%)	A/C	Cement	Water	River S	RFA
1	A5R0	1	0	5	300	300	1500	0
2	A5R25		25		300	300	1125	375
3	A5R50		50		300	300	750	750
4	A5R75		75		300	300	375	1125
5	A5R100		100		300	300	0	1500
6	A6R0	1,2	0	6	300	360	1800	0
7	A6R25		25		300	360	1350	450
8	A6R50		50		300	360	900	900
9	A6R75		75		300	360	450	1350
10	A6R100		100		300	360	0	1800
11	A7R0	1,4	0	7	300	420	2100	0
12	A7R25		25		300	420	1575	525
13	A7R50		50		300	420	1050	1050
14	A7R75		75		300	420	525	1575
15	A7R100		100		300	420	0	2100

*w/c ratio determined according to consistency (flow diameter = 16 ± 2 cm)

3 Experimental design

3.1 Mixture composition

In the preparation of mixtures, a/c and RFA ratios have been determined as variables. Levels relating with variables are given in Table 2.

As given in Table 2, 15 different mixtures have been produced within scope of experimental study, whereas there are five different RA ratios and three different A/C ratios. Material quantities relating with mortar mixtures are given in Table 3. Material amounts have been determined for a mold having approximate sizes of 40*40*160 mm (three gang mould).

3.2 Preparation of mortars and curing

In preparation of mortars, RFA being obtained from 10 and 15 cm arris cube samples has been used. RFAs have been classified in a 0–4 mm sieve opening after breaking with a crusher. The reason why grain size of RAs has not been diminished further is because great energy is needed during the process of crushing. Since it is taken as basis that an environmentally sensitive material will be developed, breaking process has been realized at optimum level. River sand has been obtained from the stream beds located in the city of Kastamonu.

In the preparation of mortars, Hobart type of laboratory mixer has been used. Mixing process has been realized as per the rules specified in EN 196–1 standard. RFA added mortars which are prepared with Hobart mixer have been placed in the molds with the help of a vibrating table. The mortars stored in the room conditions for 24 h have been removed from their molds, and they have been subjected to water cure until the day of the experiment.

3.3 Properties of fresh mortar

Flow diameters of the mortars were measured as fresh state properties (ASTM C 1437). Flow diameters of mortars being prepared as per the material quantities specified in Table 3 have been measured in X and Y directions, and an average value has been determined. Flow diameters of mortars have been fixed at the value of 16 ± 2 cm, and w/c ratios were determined accordingly.

3.4 Fresh and hardened bulk density (BD) of mortars

Fresh and hardened BDs of mortars have been obtained with arris cube samples having sizes of 50*50*50 cm (ASTM C 138). Mortars have been placed in the molds in two layers with the help of vibrating table. BD of hardened mortars have been determined after drying for 3 days at 50^{o} C in the oven. Sizes of mortars have been measured with the help of a caliper, and their volumes have been determined approximately. BD of fresh mortars has been determined by taking ASTM C 138 standard as basis.

3.5 Mechanical properties of mortars

Compressive and flexural strengths have been determined as mechanical properties of mortars (Fig. 3). Compressive and flexural strengths have been determined with prism samples having sizes of 40*40*160 mm. Mechanical properties of mortars have been determined as per ASTM C 348 and 349 standard. First of all, flexural strength of mortars (with 3

Fig. 3 Compressive and flexural strength tests which are applied to mortars

points) has been determined, and afterward, compressive strength test has been applied on the samples.

3.6 Drying shrinkage properties of mortars

Drying shrinkage properties of mortars have been determined with mortar bars having sizes of 25*25*285 mm. Drying shrinkage has been determined especially in accordance with ASTM C 596 standard. Drying shrinkage behavior has been determined by being measures in each 7th day until 56th day. Seven-day pre-curing process has been realize for mortars, and afterward, they were made subject to natural drying by being kept in clean air. Drying shrinkages of mortars have been measured with digital compressor as shown in Fig. 4.

3.7 Capillarity properties of mortars

Capillarity properties of RFA-based mortars have been determined with arris cube samples having sizes of 50*50*50 mm. Capillarity properties have been realized as per ASTM C 1585 standard. According to this standard, time-dependent water penetration depths of mortars have been determined. Lateral water absorption is prevented by applying 0.5 cm high water impermeability material to the base of the mortars. In this way, the water is provided to enter the mortar only by sorptivity way. In Fig. 5, the sorptivity test applied on the mortars is shown.

3.8 Apparent porosity properties of mortars

Porosity properties of mortars have been determined with arris cube samples having sizes of 50*50*50 mm. Porosity of mortars has been determined as per ASTM C 642 standard. In this scope, Archimedes method has been used. Standards on sample sizes

Fig. 4 Measurement of drying shrinkage of mortars

Fig. 5 Sorptivity test of mortars

Table 4 Experimental details

Properties	Standard	Shape and Size (mm)
Workability	ASTM C 1437	–
Bulk density (Hardened Mortar)	ASTM C 138	50*50*50
Mechanical properties	ASTM C 348/349	40*40*160
Drying shrinkage	ASTM C 596	25*25*285
Sorptivity	ASTMC 1585	50*50*50
Apparent porosity	ASTM C 642	50*50*50

relating with tests that have been applied to mortars having fine RA or no RA at all are given in Table 4.

4 Results and discussion

4.1 Workability properties of mortars

As flow diameters of mortars are kept fixed, w/c ratios show variations depending on a/c ratios. W/C ratios of mortars having a/c ratios of 5, 6 and 7 have been determined to be 1, 1.2 and 1.4, respectively. It is observed that as a/c ratio increases, w/c ratio also increases. The reason for this is because as the paste volume gets reduced, workability is negatively affected.

As shown in Fig. 6, flow diameters of mortars are kept constant at the value of 16 ± 2 cm. In the experimental tests being done, it is seen that increase in paste volume within the concrete structure creates a lubrication effect and it increases workability. In this way, amount of energy required to compress the concrete gets reduced (Chandara

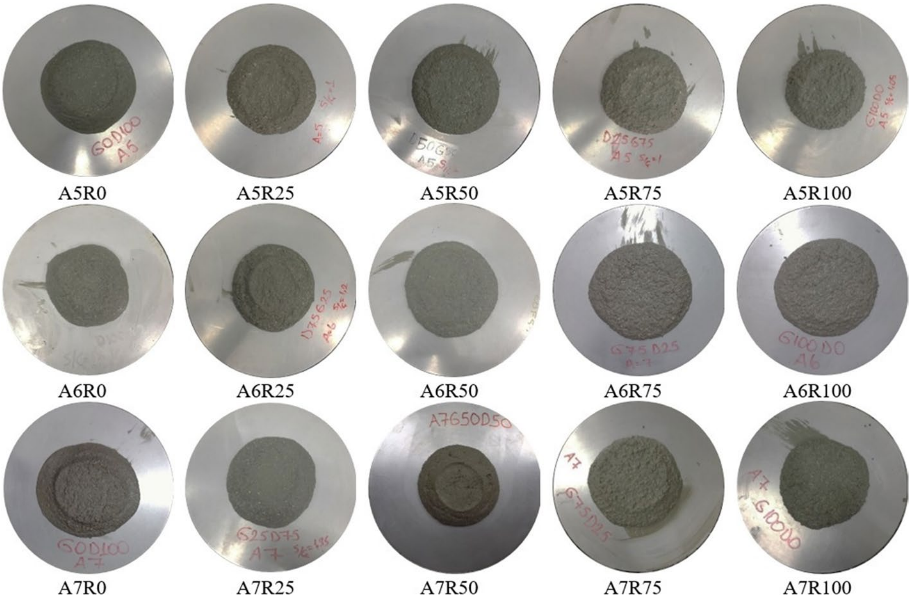
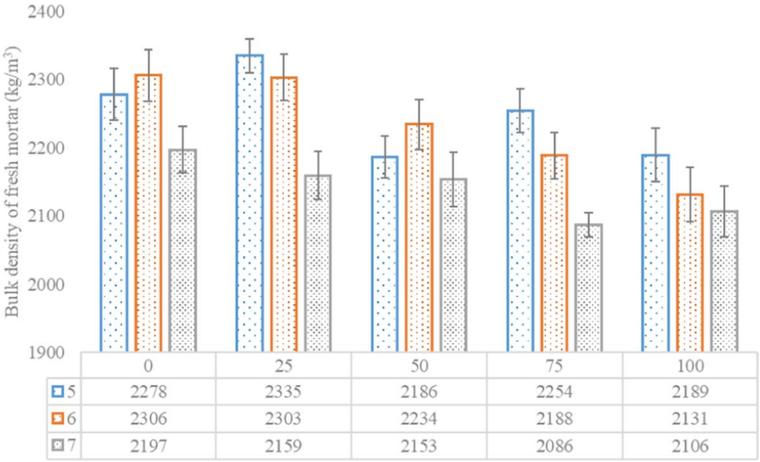

A5R0 A5R25 A5R50 A5R75 A5R100
A6R0 A6R25 A6R50 A6R75 A6R100
A7R0 A7R25 A7R50 A7R75 A7R100

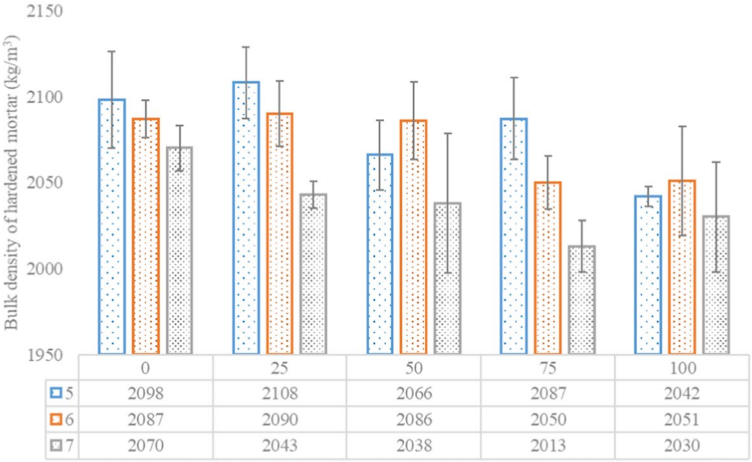
Fig. 6 Images of mortars on flow table

et al., 2010; Ravina, 1997; Zeyad et al., 2018). As a/c ratio increases, paste volume decreases and due to this reason w/c ratio of mortars increases. Besides, in the concretes produced with RFAs, w/c$_{\text{eff.}}$ ratio is reduced. For this reason workability of mixtures gets reduced as well (Quattrone et al., 2016). It is recommended for RAs that are used in concrete to be in saturated dry surface condition or to be made subject to preliminary moistening. However, there are various different methods being recommended, it is difficult to evaluate water saturation condition of RFAs in a correct way (Rueda et al., 2015; You et al., 2009). There are some disadvantages to pre-saturating the aggregates in the paste. One of the most important disadvantages is that water saturated RFAs retains water in the paste structure and cause for bleeding. As a result of this situation, with the increasing w/c ratio, properties of hardened concrete also get impacted negatively (De Oliveira & Vazquez, 1996; C. S. Poon et al., 2004; Zhao et al., 2015). It has been emphasized that it would be a more correct method to add the water that will be absorbed by RFAs within 24 h, in the form of additional water. Furthermore, water absorption process which is done 24 h beforehand requires additional work load and equipment which shows this method negatively (Corinaldesi & Moriconi, 2009; Fan et al., 2016; Jiménez et al., 2013; M. B. Leite et al., 2013; J. Silva et al., 2010).

In this study, consistencies of mortars with regard to RFA usage, where no pre-moistening process is applied, have been kept constant. While variation of RA content does not have a significant impact on workability, increase in a/c ratio has increased w/c ratio. This originates from the fact that fineness module of RA containing aggregate stack is high. For this reason, increasing RA content has not affected workability very negatively. Furthermore, abundance of material below 75 µm within RFA structure (> %3) has contributed positively for workability (> %3). Grains that were lower than 75 µm have become part of paste content and they have increased paste volume and have reduced loss of workability.



(a) BD values of fresh mortars



(b) BD values of hardened mortars

Fig. 7 BD properties of mortars having different a/c and RFA ratios

4.2 Bulk density (BD) properties of mortars

As shown in Fig. 7, as the a/c ratio of the mixture increases, BD values get reduced. While BD values of fresh mortars vary in the range of 2086–2335 kg/m^3, BD values of hardened mortars vary in the interval of 2013–2108 kg/m^3. Since specific weight of RFAs is relatively lower with respect to river sand, as RFA ratio increases, BD gets generally reduced. BD values have decreased depending on the reduction in paste volume together with the increase in a/c ratio.

While BD values of hardened mortars, a/c ratio of which is 5 vary in the interval of 2108–2042 kg/m^3, difference between BD values remain at maximum ratio of 3%. While hardened BD values vary in the interval of 2070–2013 kg/m^3 when a/c ratio is 7, difference between BD values remains maximum at the ratio of 2.8%. RFA that is used in mortar production, does not significantly impact BD values. As a result of increase in a/c ratio, difference between BD values vary in the interval of 3–5%. It is seen that BD values of hardened mortars generally remain below the value of 2100 kg/m^3. It has also been determined that when a/c ratio is 7, BD values converge quite close to 2000 kg/m^3. With 100% RFA usage, BDs get reduced by nearly 2% with respect to river sand. With the usage of RFA in masonry plaster and mortar, apparent differences have not been observed between BDs.

In the experimental study conducted by Yong and Teo, BD values of RA were found to be 9.8% lower than natural aggregates (P.C. and D.C.L, 2009). This situation has been explained with high porosity of paste that was present on RA surface. Safiuddin has reported that BD of natural aggregates varied in the interval of 1450–1750 kg/m^3 and that BD of RAs varied in the interval of 1200–1425 kg/m^3 (Safiuddin et al., 2013). In the study conducted by Ferreira et al., it was found out that with RA usage, BD of fresh mortars got reduced. Especially with 100% RA usage, BD of fresh mortars fell below the value of BD 1500 kg/m^3.

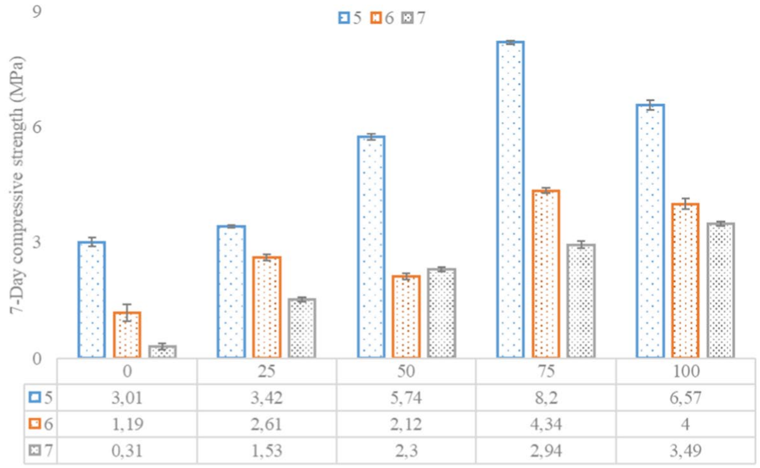
It is easier to apply as the amount of mass that can be carried for the same volume decreases in lightweight mortars. This impact makes positive contribution to the efficiency of lightweight mortars. However, since the porosity of lightweight mortars is high, their resistance to external weather conditions and aggressive environments decreases. (Saiz Martínez et al., 2016). In the study conducted by Cuenca-Moyano et al., RA replacement with the ratio of 50% has increased BD values of mortars for a certain quantity. This influence can be explained with higher uniformity coefficient of RA and higher gap filling aspect of fine grains. With the reduction in porosity values of mortars, a denser structure has been obtained. Usage of more number of fine grained aggregates for the same volume of mortar has increased BDs (G. M. Cuenca-Moyano et al., 2014).

4.3 Mechanical properties of mortars

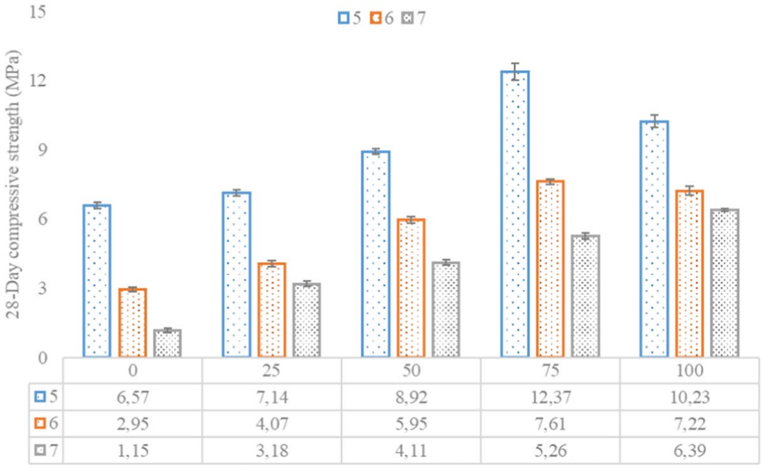
As shown in Fig. 8, in all a/c ratios usage of RA has increased 7-day compressive strengths. Especially when a/c ratio was 5 and RFA ratio was 75%, compressive strength has increased with a ratio of 173% with respect to river sand. When a/c ratio is 6 and RFA ratio is 75%, this ratio becomes 240%. Seven-day compressive strengths vary in the interval of 0.31–8.20 MPa. In all a/c ratios, in case RFA ratio was 75% and 100, compressive strengths revealed an apparent increase. However in all mortar mixtures, with increasing a/c, compressive strengths have decreased. The reason why compressive strength got reduced with increasing a/c was due to the insufficiency of paste volume.

Twenty-eight-day compressive strengths of mortars vary in the interval of 1.15–12.37 MPa values. It was observed that usage of 100% river sand reduced compressive strengths. Besides just like the case with seven-day compressive strengths, the increase in a/c ratio also reduces compressive strengths. The highest compressive strengths have been observed in 75% and 100 RFA usage. In case a/c ratio was 5, usage of 75% RFA has increased compressive strength with a ratio of 88% with respect to river sand. When a/c ratio was 7, this ratio was found to be 357%.

As a result of increase in a/c ratio, higher losses of strength are observed in mortars being produced from river sand. In the usage of 100% river sand, if a/c ratio is 6, compressive strength gets reduced with a ratio of 55% and when a/c ratio is 7, compressive strength gets reduced with ratio of 82.5%. However, in 100% RFA usage if a/c ratio is 6, compressive strength decreases with a ratio of 29.4% and when a/c ratio is 7, it gets reduced with a ratio of 37.5%. Reason why loss of strength gets reduced in RA based mortars originates



(a) 7 days



(b) 28 days

Fig. 8 Compressive strengths of mortars having different a/c and RFA ratios

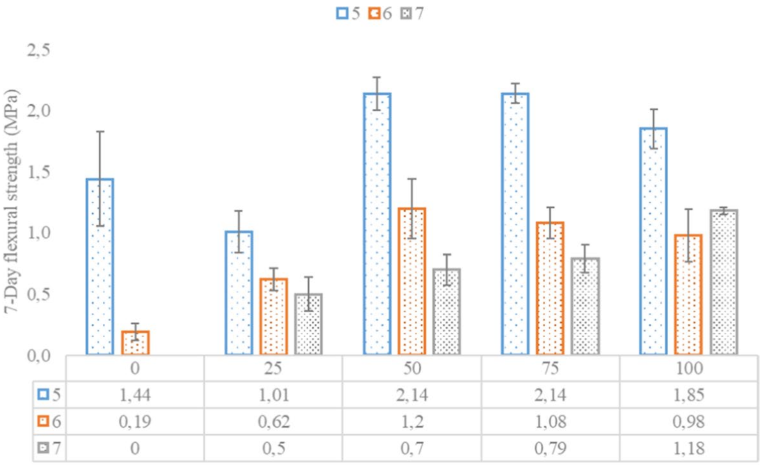
from the high fineness module (4,54) and due to abundance of grains below 75 µm. Grains below 75 µm were included in the paste and they have increased paste volume and they have contributed positively to workability even if a little bit. Besides, these grains have closed the gaps within the structure of mortar and have reduced porosity. As a result of compressive strength test, importance of filler material content within RFA structure has been seen more clearly.

It has been reported that as a result of RA usage, compressive strength got reduced with a ratio of 5–10% with respect to reference concretes in general (Safiuddin et al., 2013). However, if w/c ratio of old concrete being produced with RA is lower than w/c ratio of newly produced concrete, its compressive strength can increase with respect to reference concrete (Padmini et al., 2009). In the study conducted by M. leito, also found similar results and he has observed that there was increase in strength of RAs obtained from concretes having low w/c ratio (<0.47) (M. Leite, 2001). In the study conducted by Ahmet, with RA usage up to the ratio of 50%, increases were observed in tensile and flexural strengths (Ahmed, 2014). Cuenca-Moyano et al. have increased compressive strength by realizing pre-moistening process on RAs in masonry mortars. It has been stated that this effect occurred with the improvement of interface between RA and new cement with pre-moistening. (G. M. Cuenca-Moyano et al., 2014). In the study they conducted, Kirthika and Singh have obtained increases in mechanical properties of mortars with RFA usage up to the ratio of 30% (Kirthika & Singh, 2020). In the study they conducted, Cuenca-Moyano et al. stated that it could be possible to use RA with ratio of 100% in the production of masonry mortar (Gloria M. Cuenca-Moyano et al., 2020). Compressive strengths of concretes produced with 20% and 30% 30 RFA have shown similar features with respect to concretes produced with 100% natural fine aggregate. This impact can be explained with the particular that RA based concretes have a lower $w/c_{eff.}$ ratio with respect to reference concrete (Zega & Di Maio, 2011). In the studies being conducted, mechanical properties of aggregates come to the forefront rather than strength of cement matrix in the mortars (R. V. Silva et al., 2014). In the study conducted by Hu et al., RA usage up to 75% has increased compressive strengths. With RA usage, 60 MPa and higher level of compressive strengths have been obtained (Hu et al., 2013).

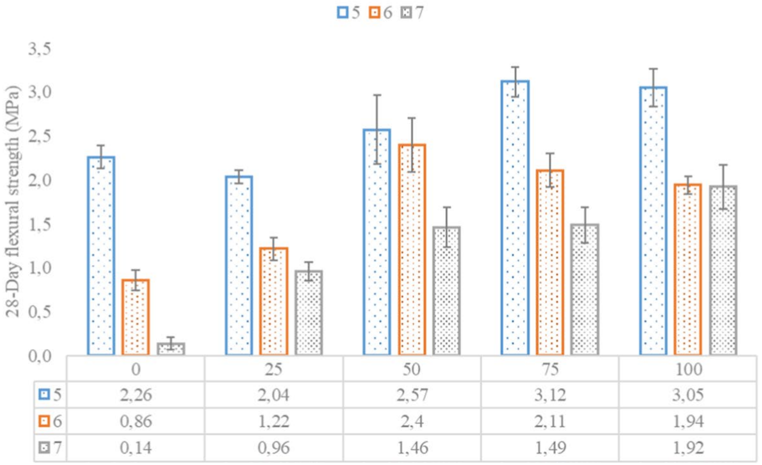
Figure 9 shows that usage of RFA with ratio of 25% in mortars having a/c ratio of 5, reduced the flexure strength by 30%. But if RFA is used by 50% and more, an increase was seen in flexural strengths. In mortars with a/c ratio of 6, increase in RFA ratio has increased seven-day flexural strengths. Especially with RFA usage of 50% and more, flexural strength has a value above 1 MPa. In case a/c ratio was 7, with the usage of 100% river sand flexural strength could not be obtained. However, with the increasing RFA content, increases were observed in flexural strength. Seven-day flexural strengths vary in the interval of 0–2.13 MPa. As a result of increase in a/c ratio, flexural strengths get reduced.

When 28-day flexural strengths are examined, it is seen that the strengths vary between values of 0.14–3.12 MPa. Especially usage of RFA with ratio of 50% and above have caused for flexural strengths to go higher than 2 MPa. If a/c ratio was 5, with usage of 100% RFA, flexural strength has increased with the ratio of 35%. If a/c ratio is 7 and RFA ratio is 100%, flexural strength has increased by 1270%. Increase in a/c ratio has affected mechanical properties negatively by reducing paste volume. This change in a/c ratio has impacted flexural strength more. Increase in RFA ratio has generally increased flexural strength. It is seen that aggregate content is more important with respect to flexural strength.

In the study conducted by Ferreira et al., usage of RA with the ratio of 25% had increased flexural strength for a certain amount. Fine material amount within RA structure fulfills a filling task, and it enables for a more durable structure to be obtained by reducing the gaps within mortar structure (Ferreira et al., 2019). Flexural strength is an important particular regarding mortars because flexural strength is an aspect which is related with shrinkage and adherence of plaster mortars (R. V. Silva et al., 2016). Due to the water accumulating between aggregate and cement paste within mortar structure (internal bleeding), interface gets weakened, as a result of which flexural strength gets reduced. RA usage and its proportional change affects flexural strength more (Behera et al., 2019). Reason for increase in flexural strength relating with RA usage has been linked to denser C–S–H gels present in the paste within RA structure (Evangelista & de Brito, 2007; Fan et al., 2016; Chi Sun Poon & Chan, 2007). In the study conducted by Salahuddin et al., RA usage up to the ratio of 50% has increased flexural strength (Salahuddin et al., 2020). According to Silva et al., self-binding characteristic of RA and the



(a) 7 days



(b) 28 days

Fig. 9 Flexural strengths of mortars having different a/c and RFA ratios

presence of cement grains that have not been subject to hydration, increases mechanical properties. Furthermore, as adherence is better in RAs having rough surfaces, increase in strength is also observed (R. V. Silva et al., 2014). In the literature, there are other studies showing that flexural strength increases with RA usage (Andreu & Miren, 2014; Liu et al., 2011).

In Fig. 10, the relationship between 28-day mortar strengths and BD of hardened mortars can be seen. With the increase in a/c ratio, it is seen that BD values and compressive strengths of mortars get reduced. The compressive strength of mortars with a/c ratio of 7 is generally below 5 MPa. In mortars having a/c ratio that is equal to 5, compressive strength is generally 7 MPa and higher. It was seen that there wasn't a powerful regression between compressive strength and BDs of mortars.

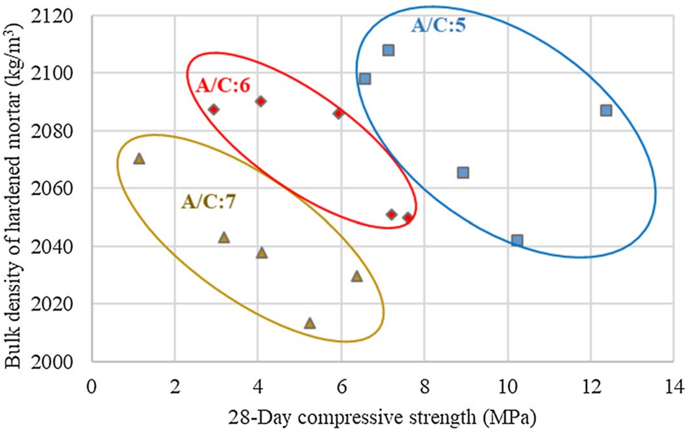


Fig. 10 BD-compressive strength (28 days) relationship of mortars having different a/c ratio

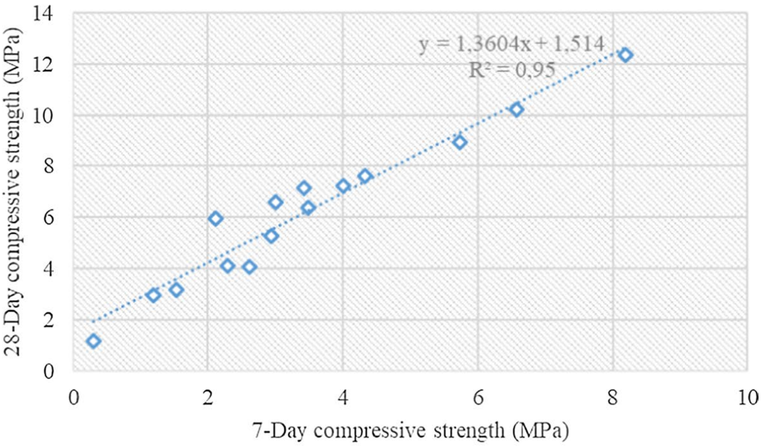
As shown in Fig. 11a, a powerful regression ($R^2 = 0.95$) has been obtained between 7- and 28-day compressive strengths. In this way, with 7-day compressive strengths prediction of nearly 28-day compressive strength can be made. As shown in Fig. 11b, a powerful regression ($R^2 = 0.91$) has also been obtained between compressive strength and flexural strength. Increases in compressive strength have caused to increase flexural strength. It is seen that when compressive strength exceeds the value of 10 MPa, flexural strengths exceed the value of 3 MPa.

4.4 Drying shrinkage properties of mortars

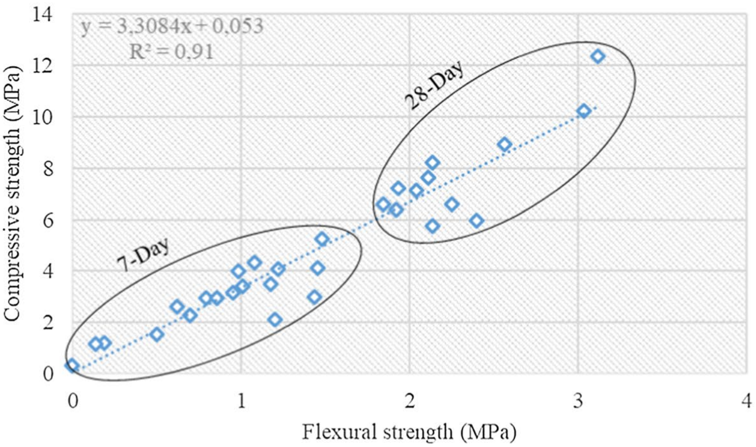
As shown in Fig. 12a, drying shrinkage of mixtures having a/c ratio of 5 has values that vary in the interval of 1710–2456 µm. In case of using 25% RFA, drying shrinkage on 56th day has been measured as 2456 µm. Besides, in case of using 100% river sand and 50% RFA, value of drying shrinkage has been determined to be nearly 2200 µm. If 75% and 100 RFA are used, it was fallen below the value of 2000 µm. 100% RFA usage in mortars has reduced drying shrinkage on 56th day by the ratio of nearly 18.3%. Drying shrinkage behavior of mortars containing RFA is generally fixed from the 14th day. However, drying shrinkage of mortars with 100% river sand content have increased in time.

Drying shrinkage values of mixtures having a/c ratio of 6, vary in the interval of 1055–2100 µm (Fig. 12b). Drying shrinkage values of mortars, apart from the mortars with 25% RFA, have fallen below the value of 2000 µm. The reason for this has been explained with increasing aggregate volume or reducing paste volume. Mortars having 100% river sand and 50% RFA, have revealed similar features as the case with mortars having a/c ratio of 5. In case the a/c ratio is 6 and 100% RFA is used, drying shrinkage on 56th day has decreased by the ratio of 40%. If RFA is used with the ratio of 75 and 100%, value of drying shrinkage was measured as nearly 1000 µm. Drying shrinkage behavior of mortars was generally fixed was initiated from 28th day onward. Usage of RFA with a ratio of more than 50% has reduced drying shrinkage of mortars.

As it is seen in Fig. 12c, when a/c ratio was 7, drying shrinkage values of mortars have fallen below the value of 1500 µm. With the increase in aggregate volume, drying shrinkage properties of mortars have improved. Drying shrinkage behaviors of mortars having



(a) Relationship of 7-28 day compressive strengths



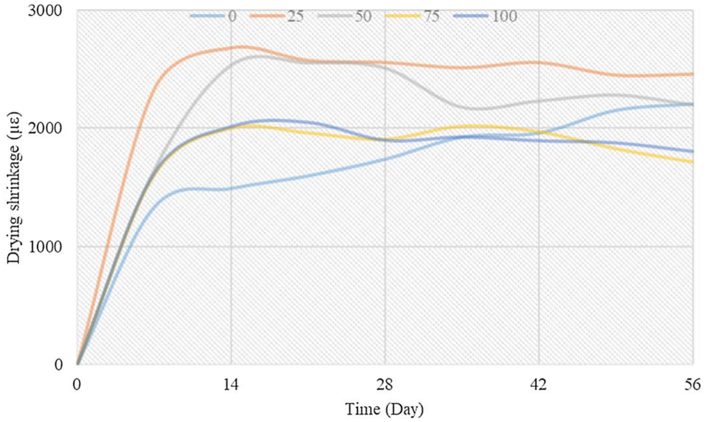
(b) Relationship of flexural-compressive strength

Fig. 11 Regression curves relating with mechanical properties of mortars

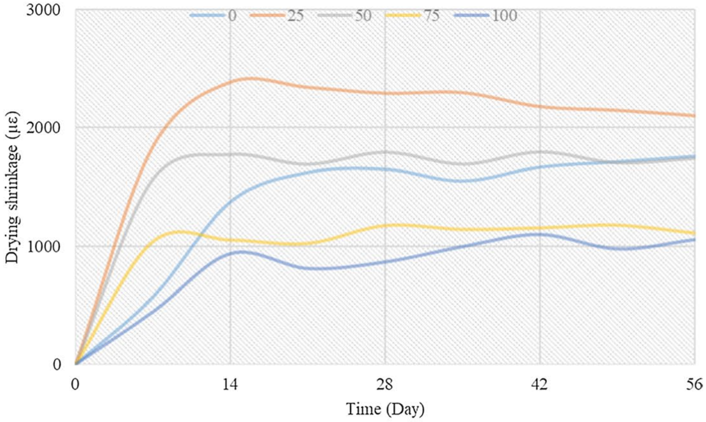
100% river sand and 25% RFA have revealed similar features and the approximate value of 1250 µm was obtained on 56th day. In case of using 100% RFA, drying shrinkage value has decreased by the ratio of 33.3% on 56th day. If RFA with a ratio of 50% or more was used, drying shrinkage values were measured as nearly 1000 µm.

When 100% RFA was used, if a/c ratio was increased from 5 to 7, drying shrinkage has decreased by the ratio of 50.7%. This ratio was determined to be 39.6% when 100% river sand was used. Increase in a/c ratio reduces drying shrinkage of mortars. Besides, with RFA usage, drying shrinkage that occur in mortars can be reduced further. Importance of increasing aggregate volume and aggregate quality can be seen in reducing drying shrinkage.

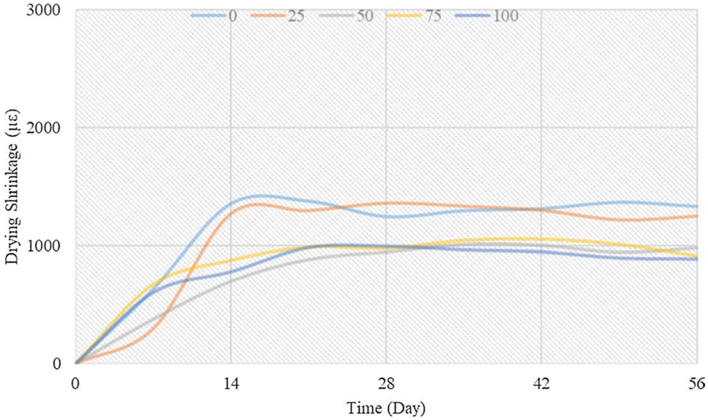
With the usage of RFA having excess water absorption properties, drying shrinkage behavior of mortars is significantly impacted. Especially in drying shrinkage of SCCs, high paste volume is an important particular for endurance (Cartuxo et al., 2015; Evangelista &



(a) A/C=5



(b) A/C=6



(c) A/C=7

Fig. 12 Time-dependent drying shrinkage behaviors of mortars de Brito, 2007). Drying shrinkage can be controlled with coarse and fine aggregate volume (W. Zhang et al., 2013). In the study conducted by Behera et al., it was determined that as compressive strength increased, drying shrinkage got reduced (Behera et al., 2019). In the study conducted by Domingo-Cabo et al., as a result of using RA with the ratio of 20%, same drying shrinkage behavior was obtained with respect to traditional concrete (Domingo-Cabo et al., 2009). By using different mixture methods, drying shrinkage of RA added mortars and concretes can be reduced (Vivian W.Y. Tam & Tam, 2007). In the study conducted by Zega and Maio with the usage of 20% RA, same drying shrinkage values were obtained with respect to traditional concrete. In case of using 30% RA, as a result of decrease in w/c$_{eff.}$ ratio, drying shrinkage values (for 180 days) have decreased a little with respect to traditional concrete (Zega & Di Maio, 2011). In the study conducted by Cong Kou et al., it has been stated that as a result of increase in compressive strength in RA based mixtures, drying shrinkage has decreased (Kou et al., 2008). Furthermore, in a study conducted by Howells et al., it was reached to the conclusion that compressive strength was one of the most effective two parameters that affected drying shrinkage of concrete (Howells et al., 2005). In a study conducted by Hu et al., usage of RFA within SCC has reduced drying shrinkage while increasing compressive strengths (Hu et al., 2013). According to Selamu et al., with RA usage both autogenous and drying shrinkage values of mortars have decreased (Abate et al., 2018). Miranda has stated that with respect to the drying shrinkage behavior of mixtures, pore size distribution which formed due to high amount of fine grains had a more important impact with respect to w/c$_{eff.}$ ratio (Miranda & Selmo, 2006). This situation is observed quite a lot in mortars where RA is used (Mesbah & Buyle-Bodin, 1999).

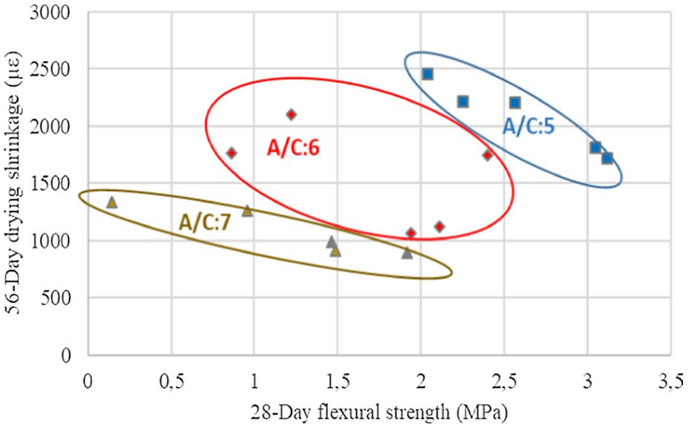
As shown in Fig. 13a, as compressive strength increases with different a/c ratios, drying shrinkage values generally get reduced. Similar situation is also valid for flexural strength. As a conclusion it is seen that compressive and flexural strengths are effective on drying shrinkage (Fig. 13b). In cases where a/c ratio is low (a/c = 5), if compressive strength was higher than 10 MPa, drying shrinkage has fallen below the value of 2000 µm.

4.5 Sorptivity properties of mortars

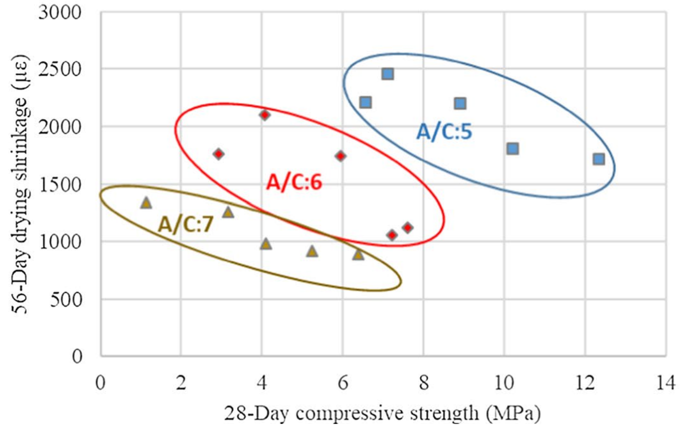
As shown in Fig. 14a, water penetration depths of mortars with a/c ratio of 5 on 28th day vary in the interval of 3.71–5.75 mm. If 100% river sand was used, water penetration depth of mortars was measured to be 5.75 mm. However, with RFA usage, water penetration depths have decreased. Especially usage of 100% RFA has reduced water penetration depths of mortars by the ratio of 20.2%. Usage of 75 and 100% RFA gas reduced water penetration depths of mortars below the value of 5 mm. Properties of mortars with 25 and 50% RA show similarities with respect to their water penetration depths.

In case a/c ratio is 6, water penetration depths of mortars on 28th day vary between 3.80 and 7.34 mm. With respect to water penetration depth, 100% river sand, 25 and 50% RFA added mortars have shown similar features. It was found that water penetration depth of 100% river sand and 50% RFA added mortars was higher than 7 mm. In case of using 100% RFA, water penetration depth had decreased by the ratio of 48.2%. In the mortars where RFA with ratio of 75% was used, water penetration depth has decreased below the value of 5 mm.

In mortars having a/c ratio that is equal to 7, water penetration depth vary in the interval of 8.70–15.51 mm. Especially water penetration depths of 100% river sand and 25% RFA added mortars on 28th day are higher than 15 mm. In mortars where 100% RFA has been



(a) Drying shrinkage-compressive strength



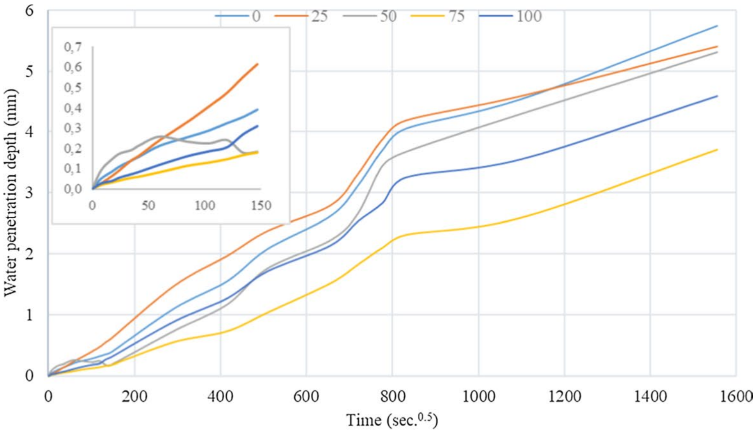
(b) Drying shrinkage-flexural strength

Fig. 13 Relationship of drying shrinkage with mechanical properties

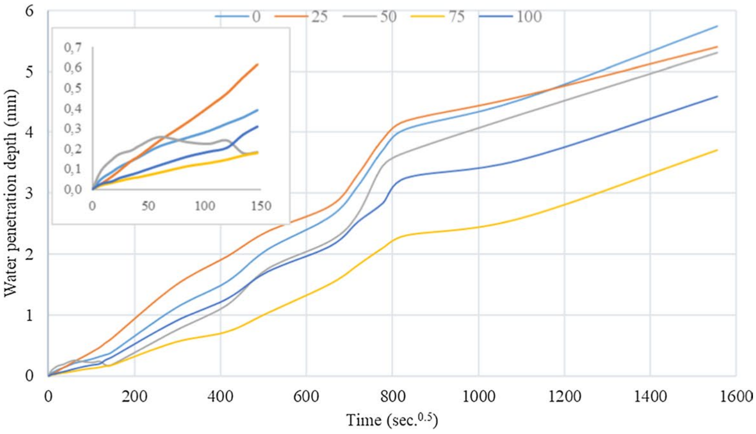
used, water penetration depth has decreased by the ratio of 43.9%. Mortars in which 50 and 75% RFA are used, reveal similar features and they have approximate water penetration depth of 13 mm.

With the increase in a/c ratio, water penetration depths of mortars get increased. Especially usage of RFA with ratios of 75 and 100% reduce water penetration depths of mortars. The reason for this originates from the presence of filler material within RFA structure. Usage of RFA with a low ratio such as 25% has not been very effective in reducing water penetration depth. Besides, it was observed that mortars with high drying shrinkage values, had higher water penetration depth values. It has been determined that mortars with 75 and 100% RFA having low values of water penetration depths also had high compressive strength.

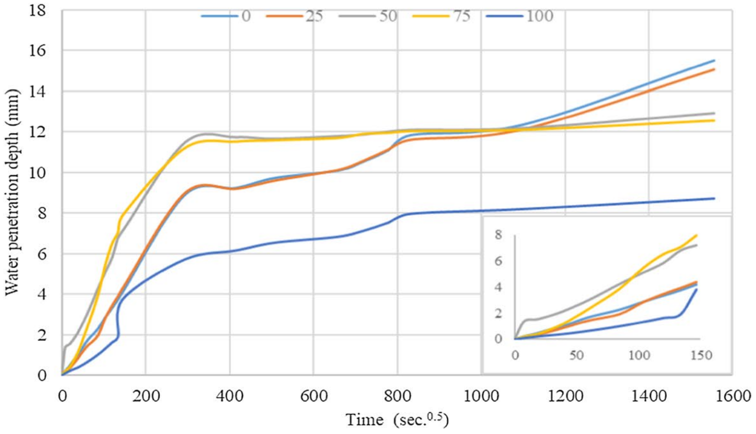
Zega and Maio have stated that in the sorptivity tests of concretes with RFA, values close to traditional concrete were obtained. It has especially been stated that sorptivity permeability coefficient obtained with RFA added concretes was in conformity with Argentina



(a) A/C=5



(b) A/C=6

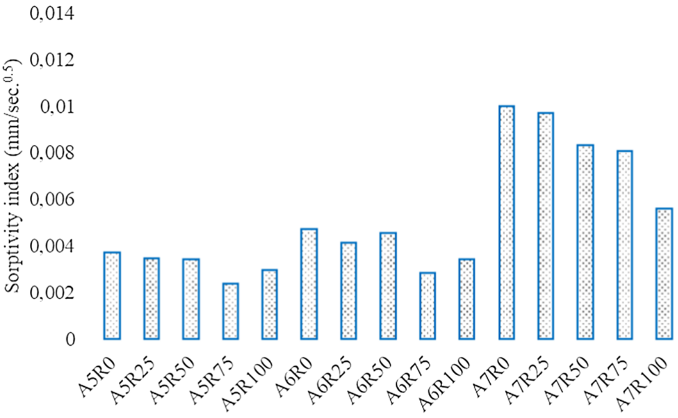


(c) A/C=7

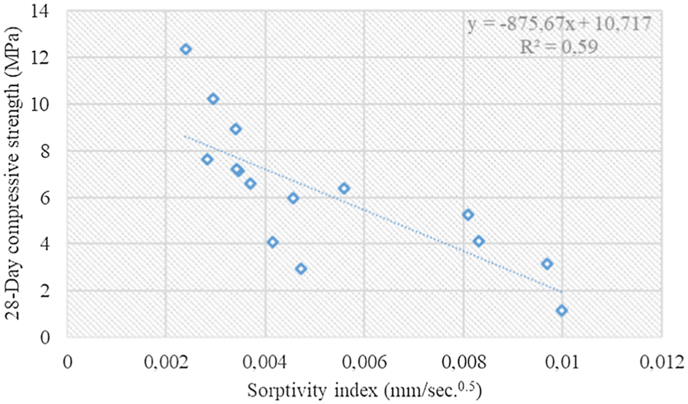
Fig. 14 Time-dependent water penetration depths of mortars

Regulations (Zega & Di Maio, 2011). In certain studies being made, it was observed that dense C–S–H gel structure coated micro pores better and that sorptivity was reduced as a result of this (Evangelista & de Brito, 2007; Khatib, 2005; Chi Sun Poon & Chan, 2007). According to Tam and Lee, absorption properties of cement paste are more with respect to aggregate. The more the cement paste content that RA has, the lower their densities are and the higher their water absorption and porosity are (Tam & Le, 2008). In a study conducted by Abdel-Hay, sorptivity permeability coefficients of concretes where RA was used and that were made subject to air curing, got reduced. Concretes with RA to which water curing was applied, showed features similar to traditional concrete (Abdel-Hay, 2017). In the study conducted by Jaskulski et al., sorptivity properties of concretes being produced by using RA showed similarity to concretes being produced with normal aggregate (Jaskulski et al., 2016).

As shown in Fig. 15a, increase in a/c ratio increases the sorptivity. The reason for this can be explained with decreasing paste volume or increasing aggregate volume. Increase in compressive strength reduces the sorptivity. It has been observed that compressive strength



(a) Sorptivity coefficients of mortars



(b) Relationship of sorptivity-compressive strength

Fig. 15 Sorptivity properties of mortars is important in water absorption through sorptivity means (Fig. 15b). Usage of RFA with ratios of 75 and 100% in mortars with a/c ratio that is equal to 5, has caused for sorptivity value to fall below 0.003 mm/san$^{0.5}$. If a/c ratio is 7 in the usage of 100% RFA, this causes for sorptivity value to increase by nearly 93%. For this reason in RFA added mortars, more attention should be paid to a/c ratio. Because in mortars with compressive strength in the interval of 2–4 MPa, it is seen that sorptivity value is below 0.005 mm/san$^{0.5}$.

4.6 Apparent porosity Property of mortars

As shown in Fig. 16, apparent porosity values of mortars vary between 18.98 and 25.93%. It is generally observed that as a/c ratio in mortar structure increases, apparent porosity values also increase. The reason for this can be explained with increasing aggregate volume. In particular, the porosity of cement paste surrounding RFA causes for apparent porosity value to increase because absorptivity of cement paste is higher with respect to aggregate. Increase in apparent porosity with the increase in RFA content could be explained in this way. 100% RFA usage in mortars with a/c ratio that is equal to 5, apparent porosity value has increased by the ratio of 33.6%. But when a/c ratio is 7 and 100% RFA is used, this has caused for porosity value to increase by 8%. This situation can be explained with the decrease in paste volume as a result of increase in a/c ratio. With the decrease in paste volume, differences between apparent porosity values of mortars also decrease. With regard to apparent porosity values, it is seen that mortars where 75 and 100% RFA are used have shown similar features. With regard to mortars where 100% river sand was used, nearest apparent porosity values were obtained in 25% RFA added mortars. Generally, the increase in a/c an RFA ratio increase apparent porosity values. Besides as w/c ratio also increases as being parallel to a/c ratio, apparent porosity value has shown an increase. However, grains below 75 μm that were within RFA structure have relatively reduced this impact.

In the study conducted by Contreras et al., concretes having different features were produced with construction and urban transformation wastes. While apparent porosity values of concretes vary between 26.03% and 32.97%, their compressive strengths vary in the interval of 4.12–7.73 MPa (Contreras et al., 2016). In the study conducted by Amorim Júnior et al., freeze–thaw properties of RA-added concretes have been examined. In the study being conducted, with the increase in RA ratio used within the concrete, apparent

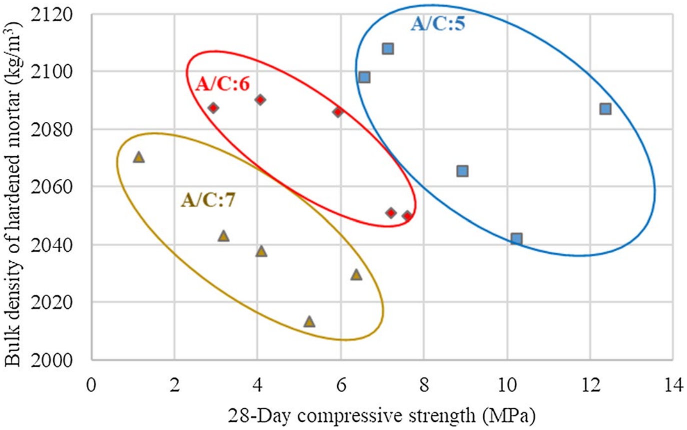
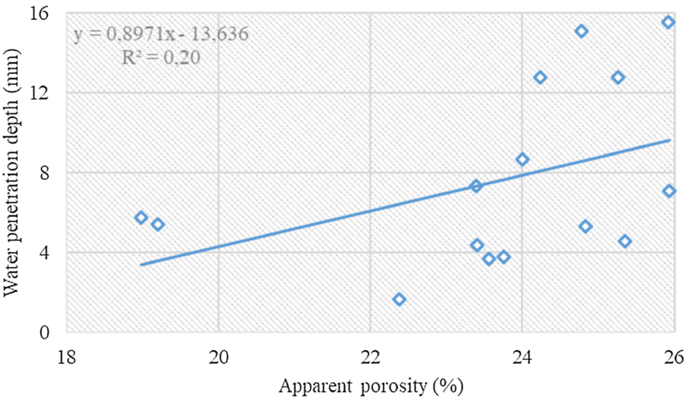


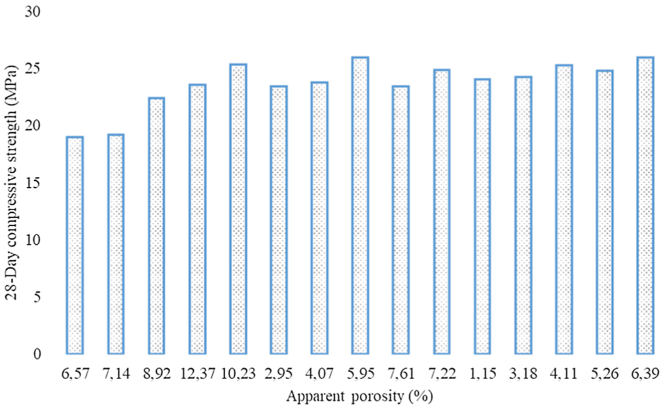
Fig. 16 Apparent porosity values of mortars having different a/c and RFA ratios

porosity values of concretes have increased. The reason for this has been explained with the presence of mortar having an approximate ratio of 44% that surrounded RA (Amorim Júnior et al., 2018). According to Etxeberria et al., porosity of old paste/mortar on the surface of RA is very high. As a conclusion, the higher the replacement of natural aggregate with RA, the more the total porosity of mixture will be (Etxeberria et al., 2006). In the study conducted by Lima et al., it was seen that as a result of RA usage, apparent porosity values varied in the interval of 20.3–30.8%. As porosity value increases, compressive strengths generally decrease (Lima & Leite, 2012). In the study conducted by Kirthika and Singh, RA usage up to the ratio of 50% has reduced porosity values (Kirthika & Singh, 2020). Similar results were also observed in the study conducted by Ren et al. (Ren et al., 2020).

Figure 17a shows that the relationship between porosity and water penetration depth is weak ($R^2 = 0.20$). But generally, the increase in porosity also increases water penetration depth. It is especially seen that mortars having water penetration depth that is higher than 12 mm, also have porosity values that are higher than 24%. No correlation could be



(a) Water penetration depth-Porosity



(b) Compressive strength (28 days)-Porosity

Fig. 17 Regression features relating with porosity values of mortars obtained between porosity and compressive strength. It is known that in traditional concrete, as porosity decreases, compressive strength increases. However in this study, such a relationship could not be obtained between compressive strength and apparent porosity. While porosity value of 75% added mortar with compressive strength of 12.4 MPa was 23.56%, compressive strength of mortar with 100% river sand having porosity value of 18.98% was found to be 6.6 MPa. This situation has occurred due to the porous mortar around RFA. Besides the production of aggregates that were selected as RFA with a low w/c ratio at the beginning has also been effective. In the current study being made w/c ratios of mortars vary in the range of 1.0–1.4. Furthermore, since RFAs have a rougher surface with respect to river sand, their adherence with cement is more and this causes for compressive strength to increase. The fact that RFAs are obtained from limestone aggregate at the beginning and that these aggregates have a higher strength with respect to river sands also constitutes an important factor. More abundance of grains lower than the size of 75 micron in RFA with respect to river sand is another factor that increases the strength. Because these grains increase compressive strength by both providing micro filler impact and pozzolanic reaction. Porosity of paste surrounding RFA increases apparent porosity of mortars but cement/water ratio of old paste, surface roughness, fineness module of aggregate, aggregate root and similar factors contribute to compressive strength.

Nakataki and Tem stated that old mortar on RA surface would negatively impact the adherence between aggregate and new paste. Because a new interface region forms between old and new paste, which negatively affects adherence (Nagataki et al., 2004; Vivian W.Y. Tam et al., 2005). On the other hand, old cement paste, RA and new cement paste enable additional hydration at interface region and as a result of this, adherence between aggregate and cement matrix increases (Khalaf & DeVenny, 2004). In the studies conducted by Chen and Wang and Zimbelmann, it has been asserted that adherence between aggregate and mortar matrix depended on three different factors. These are namely occurrence of mechanical keying by cement hydration products on rough aggregate surface, epitaxial growth of hydration products on some of the aggregate surfaces, and formation of physicochemical bond between hydrated cement paste and aggregate (Zhi Yuan & Jian Guo, 1987; Zimbelmann, 1985). In the study conducted by Seo and Choi, it is seen that sufficient amount of old paste on RA surface increases adherence. Besides, adherence ratio of old mortar can show variations depending on the size of RA (Seo & Choi, 2014).

Wastes forming in urban transformation can be classified as coarse or RFA and filler RA. In particular, the number of researches relating with fine and filler RA is quite limited. 25 to 30% of wastes that form are released as filler RA (Kasai, 2004). Filler RAs have a mixed mineral composition consisting of quartz, calcite, ethyngitis, unhydrated cement grains, calcium silicate hydrate and calcium aluminate hydrated. (Rakhimova & Rakhimov, 2015). Unhydrated cement grains within filler RA make positive contribution for hydration with nucleation effect and increase compressive strength (Thomas et al., 2009). Beixing et al. have stated that crushed stones obtained from rocks had a rougher surface with respect to river sands. Crushed limestone aggregates contain more number of grains having size smaller than 75 microns, due to the breaking process with respect to river sands. Due to the high level of surface roughness that crushed limestone aggregates have, increases were seen in compressive and flexural strengths (Li et al., 2011). Results obtained for crushed limestone aggregate can also be valid for RA.

Another reason for increase in compressive strength with the usage of fine RA has been shown as contribution that is made for internal curing. The presence of water being absorbed within the pores at the beginning during hydration stage of cement materials can increase compressive strength. Besides, unhydrated cement grains within structure of RAs that also take part in pozzolanic reactions also increase the strength (Evangelista & de Brito, 2007; Khatib, 2005).

5 Conclusions

RFA-added and non-added mortars have been produced by considering value of 16 ± 2 cm as basis for flow diameters. For this reason, as a/c ratio of mortars increase, w/c ratios also increase. Reduction in paste volume has decreased workability of mortars and for this reason an increase was seen in w/c ratio. Increase in RFA content has been very effective on workability. As a/c and w/c ratios increase, both fresh and hardened BDs of mortars get reduced. The reason for this can be explained with usage of RFA which has a relatively lower specific weight with respect to river sand.

RFA usage in the production of mortars has increased 7- and 28-day compressive strengths. Usage of RFA up to the ratio of 75% increases compressive strengths. As a result of 100% RFA usage, compressive strength has decreased with respect to mortars having 75% RFA but high values were again obtained from reference mortar. Addition of RFA with regard to 7- and 28-day flexural strengths generally enable increase in strength. Surface roughness of RFAs and low w/c ratio have also made positive contribution to flexural strength. With the increase in a/c ratio, flexural and compressive strengths decrease. Decrease in paste volume has negatively impacted mechanical properties.

As the a/c ratio of the mortars increases until the 56th day, the drying shrinkage decreases. As a result of decrease in paste volume, drying shrinkage values have decreased. Besides in case RFA content is 50% or more, drying shrinkage values decrease. Drying shrinkage behavior of 100% river sand and 25% RFA added mortars generally reveal similar features. It has been observed that mortars with high level of compressive strength gave rise to lower drying shrinkage.

As a/c ratio of mortars, sorptivity properties of which are examined increase, water penetration depth shows an increase. Because as paste volume decreases, porosity within mortar structure increases and water penetration depth also shows an increase. If RFA ratio is 75 and 100%, water penetration depths generally decrease.

Apparent porosity of mortars increase as a/c ratio increases. Porosity increases depending on the decrease in paste volume. Besides as RFA ratio increases, porosity increase that can be neglected occurs. The reason for this is because old mortar on RFA surface has high porosity.

As a conclusion, RFA usage has made positive contribution to the properties of mortars. High heterogeneity of RFAs restricts its use in structural concrete production. However, in applications such as mortar and plaster that are not structural, it can be easier to dispose RFAs. Today, it will be possible to use urban transformation wastes in mortar and plaster applications in order to protect natural resources in concrete production. In addition, mortars containing RFA can be used in the production of ready-mixed plaster.

Acknowledgements This study has been supported by TUBITAK within scope of 2209 project (University Students Foreign Research Projects Support Program). Authoers thank to TUBITAK that has contributed for the project to be completed.

Author contributions GK involved in design, resources, and writing; MT involved in materials, data collection and/or processing; BB involved in materials, data collection and/or processing; OYB involved in materials, literature search, analysis and/or interpretation.

Declarations

Conflict of ınterest The authors declare no conflict of interest.

References

Abate, S. Y., Song, K. I., Song, J. K., Lee, B. Y., & Kim, H. K. (2018). Internal curing effect of raw and carbonated recycled aggregate on the properties of high-strength slag-cement mortar. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2018.01.035

Abdel-Hay, A. S. (2017). Properties of recycled concrete aggregate under different curing conditions. *HBRC Journal, 13*(3), 271–276. https://doi.org/10.1016/J.HBRCJ.2015.07.001

Ahmed, S. F. U. (2014). Properties of concrete containing recycled fine aggregate and fly ash. *Journal of Solid Waste Technology and Management, 40*(1), 70–78. https://doi.org/10.5276/JSWTM.2014.70

Amorim Júnior, N. S., Silva, G. A. O., & Ribeiro, D. V. (2018). Effects of the incorporation of recycled aggregate in the durability of the concrete submitted to freeze-thaw cycles. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2017.12.076

Andreu, G., & Miren, E. (2014). Experimental analysis of properties of high performance recycled aggregate concrete. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2013.11.054

Behera, M., Minocha, A. K., & Bhattacharyya, S. K. (2019). Flow behavior, microstructure, strength and shrinkage properties of self-compacting concrete incorporating recycled fine aggregate. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2019.116819

Braga, M., De Brito, J., & Veiga, R. (2012). Incorporation of fine concrete aggregates in mortars. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2012.06.031

Carro-López, D., González-Fonteboa, B., De Brito, J., Martínez-Abella, F., González-Taboada, I., & Silva, P. (2015). Study of the rheology of self-compacting concrete with fine recycled concrete aggregates. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2015.08.091

Cartuxo, F., De Brito, J., Evangelista, L., Jiménez, J. R., & Ledesma, E. F. (2015). Rheological behaviour of concrete made with fine recycled concrete aggregates - Influence of the superplasticizer. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2015.03.119

Chandara, C., Sakai, E., Azizli, K. A. M., Ahmad, Z. A., & Hashim, S. F. S. (2010). The effect of unburned carbon in palm oil fuel ash on fluidity of cement pastes containing superplasticizer. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2010.02.036

Contreras, M., Teixeira, S. R., Lucas, M. C., Lima, L. C. N., Cardoso, D. S. L., da Silva, G. A. C., Gregório, G. C., De Souza, A. E., & Dos Santos, A. (2016). Recycling of construction and demolition waste for producing new construction material (Brazil case-study). *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2016.07.044

Corinaldesi, V., & Moriconi, G. (2009). Behaviour of cementitious mortars containing different kinds of recycled aggregate. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2007.12.006

Cuenca-Moyano, G. M., Martín-Morales, M., Valverde-Palacios, I., Valverde-Espinosa, I., & Zamorano, M. (2014). Influence of pre-soaked recycled fine aggregate on the properties of masonry mortar. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2014.07.098

Cuenca-Moyano, G. M., Martín-Pascual, J., Martín-Morales, M., Valverde-Palacios, I., & Zamorano, M. (2020). Effects of water to cement ratio, recycled fine aggregate and air entraining/plasticizer admixture on masonry mortar properties. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2019.116929

de Brito, J., & Saikia, N. (2013). Recycled Aggregate in Concrete: Use of Industrial, Construction and Demolition Waste. *Green Energy and Technology*. https://doi.org/10.1007/978-1-4471-4540-0

De Oliveira, M. B., & Vazquez, E. (1996). The influence of retained moisture in aggregates from recycling on the properties of new hardened concrete. *Waste Management*. https://doi.org/10.1016/S0956-053X(96)00033-5

Domingo-Cabo, A., Lázaro, C., López-Gayarre, F., Serrano-López, M. A., Serna, P., & Castaño-Tabares, J. O. (2009). Creep and shrinkage of recycled aggregate concrete. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2009.02.018

EN 206–1. (2000). *EN 206–1. Performance-Based Specifications and Control of Concrete Durability. Concrete. Part 1, Specification, performance, production and conformity.*

Etxeberria, M., Vázquez, E., & Marí, A. (2006). Microstructure analysis of hardened recycled aggregate concrete. *Magazine of Concrete Research*. https://doi.org/10.1680/macr.2006.58.10.683

Etxeberria, M., Vázquez, E., Marí, A., & Barra, M. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and Concrete Research*. https://doi.org/10.1016/j.cemconres.2007.02.002

Eurostat. (2018). Eurostat Statistics Explained. *Eurostat Statistics Explained.*

Evangelista, L., & de Brito, J. (2007). Mechanical behaviour of concrete made with fine recycled concrete aggregates. *Cement and Concrete Composites*. https://doi.org/10.1016/j.cemconcomp.2006.12.004

Evangelista, L., & de Brito, J. (2010). Durability performance of concrete made with fine recycled concrete aggregates. *Cement and Concrete Composites*. https://doi.org/10.1016/j.cemconcomp.2009.09.005

Evangelista, L., Guedes, M., De Brito, J., Ferro, A. C., & Pereira, M. F. (2015). Physical, chemical and mineralogical properties of fine recycled aggregates made from concrete waste. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2015.03.112

Fan, C. C., Huang, R., Hwang, H., & Chao, S. J. (2016). Properties of concrete incorporating fine recycled aggregates from crushed concrete wastes. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2016.02.154

Fernández-Ledesma, E., Jiménez, J. R., Ayuso, J., Corinaldesi, V., & Iglesias-Godino, F. J. (2016). A proposal for the maximum use of recycled concrete sand in masonry mortar design. *Materiales De Construccion*. https://doi.org/10.3989/mc.2016.08414

Ferreira, R. L. S., Anjos, M. A. S., Nóbrega, A. K. C., Pereira, J. E. S., & Ledesma, E. F. (2019). The role of powder content of the recycled aggregates of CDW in the behaviour of rendering mortars. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2019.03.058

Geng, J., & Sun, J. (2013). Characteristics of the carbonation resistance of recycled fine aggregate concrete. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2013.08.090

Guo, H., Shi, C., Guan, X., Zhu, J., Ding, Y., Ling, T. C., Zhang, H., & Wang, Y. (2018). Durability of recycled aggregate concrete—A review. *Cement and Concrete Composites*. https://doi.org/10.1016/j.cemconcomp.2018.03.008

Guo, Y., Qian, J., & Wang, X. (2013). Pore structure and influence of recycled aggregate concrete on drying shrinkage. *Mathematical Problems in Engineering*. https://doi.org/10.1155/2013/912412

Howells, R. W., Lark, R. J., & Barr, B. I. G. (2005). A sensitivity study of parameters used in shrinkage and creep prediction models. *Magazine of Concrete Research*. https://doi.org/10.1680/macr.2005.57.10.589

Hu, J., Wang, Z., & Kim, Y. (2013). Feasibility study of using fine recycled concrete aggregate in producing self-consolidation concrete. *Journal of Sustainable Cement-Based Materials*. https://doi.org/10.1080/21650373.2012.757832

Jaskulski, R., Waszak, O. A., & Kubissa, W. (2016). Model for Forecasting the Sorptivity of Concretes with Recycled Concrete Aggregate. *Procedia Engineering*. https://doi.org/10.1016/j.proeng.2016.08.109

Jiménez, J. R., Ayuso, J., López, M., Fernández, J. M., & De Brito, J. (2013). Use of fine recycled aggregates from ceramic waste in masonry mortar manufacturing. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2012.11.036

Kasai, Y. (2004). Recent trends in recycling of concrete waste and use of recycled aggregate concrete in Japan. *Recycling Concrete and Other Materials for Sustainable Development, 219*, 11–34.

Katz, A., & Kulisch, D. (2017). Performance of mortars containing recycled fine aggregate from construction and demolition waste. *Materials and Structures/materiaux Et Constructions*. https://doi.org/10.1617/s11527-017-1067-x

Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). *What a waste 2.0: A global snapshot of solid waste management to 2050*. Washington, DC: World Bank.

Khalaf, F. M., & DeVenny, A. S. (2004). Recycling of demolished masonry rubble as coarse aggregate in concrete: Review. *Journal of Materials in Civil Engineering*. https://doi.org/10.1061/(ASCE)0899-1561(2004)16:4(331)

Khatib, J. M. (2005). Properties of concrete incorporating fine recycled aggregate. *Cement and Concrete Research*. https://doi.org/10.1016/j.cemconres.2004.06.017

Kirthika, S. K., & Singh, S. K. (2020). Durability studies on recycled fine aggregate concrete. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2020.118850

Kou, S. C., & Poon, C. S. (2009). Properties of concrete prepared with crushed fine stone, furnace bottom ash and fine recycled aggregate as fine aggregates. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2009.02.009

Kou, S. C., Poon, C. S., & Chan, D. (2008). Influence of fly ash as a cement addition on the hardened properties of recycled aggregate concrete. *Materials and Structures/materiaux Et Constructions*. https://doi.org/10.1617/s11527-007-9317-y

Kou, S. C., Poon, C. S., & Wan, H. W. (2012). Properties of concrete prepared with low-grade recycled aggregates. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2012.06.060

Kwan, W. H., Ramli, M., Kam, K. J., & Sulieman, M. Z. (2012). Influence of the amount of recycled coarse aggregate in concrete design and durability properties. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2011.06.059

Lee, S. T. (2009). Influence of recycled fine aggregates on the resistance of mortars to magnesium sulfate attack. *Waste Management*. https://doi.org/10.1016/j.wasman.2009.04.002

Leite, M. (2001). Evaluation of the mechanical properties of concretes made with recycled aggregates form construction and demolition waste.

Leite, M. B., Figueire Do Filho, J. G. L., & Lima, P. R. L. (2013). Workability study of concretes made with recycled mortar aggregate. *Materials and Structures/Materiaux et Constructions*. https://doi.org/10.1617/s11527-012-0010-4

Li, B., Ke, G., & Zhou, M. (2011). Influence of manufactured sand characteristics on strength and abrasion resistance of pavement cement concrete. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2011.04.004

Lima, P. R. L., & Leite, M. B. (2012). Influence of CDW recycled aggregate on drying shrinkage of mortar. *Open Journal of Civil Engineering*. https://doi.org/10.4236/ojce.2012.22009

Liu, Q., Xiao, J., & Sun, Z. (2011). Experimental study on the failure mechanism of recycled concrete. *Cement and Concrete Research*. https://doi.org/10.1016/j.cemconres.2011.06.007

Lovato, P. S., Possan, E., Molin, D. C. C. D., Masuero, Â. B., & Ribeiro, J. L. D. (2012). Modeling of mechanical properties and durability of recycled aggregate concretes. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2011.06.043

Martín-Morales, M., Zamorano, M., Ruiz-Moyano, A., & Valverde-Espinosa, I. (2011). Characterization of recycled aggregates construction and demolition waste for concrete production following the Spanish Structural Concrete Code EHE-08. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2010.07.012

Martínez, I., Etxeberria, M., Pavón, E., & Díaz, N. (2018). Influence of demolition waste fine particles on the properties of recycled aggregate masonry mortar. *International Journal of Civil Engineering*. https://doi.org/10.1007/s40999-017-0280-x

Mesbah, H. A., & Buyle-Bodin, F. (1999). Efficiency of polypropylene and metallic fibres on control of shrinkage and cracking of recycled aggregate mortars. *Construction and Building Materials*. https://doi.org/10.1016/S0950-0618(99)00047-1

Miranda, L. F. R., & Selmo, S. M. S. (2006). CDW recycled aggregate renderings: Part I—Analysis of the effect of materials finer than 75 µm on mortar properties. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2005.02.025

Nagataki, S., Gokce, A., Saeki, T., & Hisada, M. (2004). Assessment of recycling process induced damage sensitivity of recycled concrete aggregates. *Cement and Concrete Research*. https://doi.org/10.1016/j.cemconres.2003.11.008

Neno, C., Brito, J. D., & Veiga, R. (2014). Using fine recycled concrete aggregate for mortar production. *Materials Research*. https://doi.org/10.1590/S1516-14392013005000164

Olorunsogo, F. T., & Padayachee, N. (2002). Performance of recycled aggregate concrete monitored by durability indexes. *Cement and Concrete Research*. https://doi.org/10.1016/S0008-8846(01)00653-6

Yong, P. C., & Teo, D. C. L. (2009). Utilisation of recycled aggregate as coarse aggregate in concrete. *Journal of Civil Engineering, Science and Technology.*, *1*, 1–6. https://doi.org/10.33736/jcest.60.2009

Padmini, A. K., Ramamurthy, K., & Mathews, M. S. (2009). Influence of parent concrete on the properties of recycled aggregate concrete. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2008.03.006

Pereira, P., Evangelista, L., & De Brito, J. (2012). The effect of superplasticisers on the workability and compressive strength of concrete made with fine recycled concrete aggregates. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2011.10.050

Poon, C. S., Shui, Z. H., Lam, L., Fok, H., & Kou, S. C. (2004). Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. *Cement and Concrete Research*. https://doi.org/10.1016/S0008-8846(03)00186-8

Poon, C. S., & Chan, D. (2007). The use of recycled aggregate in concrete in Hong Kong. *Resources, Conservation and Recycling*. https://doi.org/10.1016/j.resconrec.2006.06.005

Quattrone, M., Cazacliu, B., Angulo, S. C., Hamard, E., & Cothenet, A. (2016). Measuring the water absorption of recycled aggregates, what is the best practice for concrete production? *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2016.07.019

Raeis Samiei, R., Daniotti, B., Pelosato, R., & Dotelli, G. (2015). Properties of cement-lime mortars vs. cement mortars containing recycled concrete aggregates. *Construction and Building Materials., 84*, 84–94. https://doi.org/10.1016/j.conbuildmat.2015.03.042

Rahal, K. (2007). Mechanical properties of concrete with recycled coarse aggregate. *Building and Environment*. https://doi.org/10.1016/j.buildenv.2005.07.033

Rakhimova, N. R., & Rakhimov, R. Z. (2015). Hydrated Portland cement as an admixture to alkali-activated slag cement. *Advances in Cement Research*. https://doi.org/10.1680/adcr.13.00072

Ravina, D. (1997). Properties of fresh concrete incorporating a high volume of fly ash as partial fine sand replacement. *Materials and Structures/materiaux Et Constructions*. https://doi.org/10.1007/bf02524775

Ren, P., Li, B., Yu, J.-G., & Ling, T.-C. (2020). Utilization of recycled concrete fines and powders to produce alkali-activated slag concrete blocks. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2020.122115

RILEM. (1994). TC 121-DRG guidance for demolition and reuse of concrete and masonry—Specifications for concrete with recycled aggregates. *Materials and Structures*. https://doi.org/10.1007/BF02473217

Rodrigues, F., Carvalho, M. T., Evangelista, L., & De Brito, J. (2013). Physical-chemical and mineralogical characterization of fine aggregates from construction and demolition waste recycling plants. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2013.02.023

Rueda, J., Dapena, E., Alaejos, P., & Menéndez De Llano, S. (2015). An accelerated test to assess the quality of recycled concrete sands based on their absorption capacity. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2014.12.039

Safiuddin, M., Alengaram, U. J., Rahman, M. M., Salam, M. A., & Jumaat, M. Z. (2013). Use of recycled concrete aggregate in concrete: A review. *Journal of Civil Engineering and Management*. https://doi.org/10.3846/13923730.2013.799093

Sagoe-Crentsil, K. K., Brown, T., & Taylor, A. H. (2001). Performance of concrete made with commercially produced coarse recycled concrete aggregate. *Cement and Concrete Research*. https://doi.org/10.1016/S0008-8846(00)00476-2

Saiz Martínez, P., González Cortina, M., Fernández Martínez, F., & Rodríguez Sánchez, A. (2016). Comparative study of three types of fine recycled aggregates from construction and demolition waste (CDW), and their use in masonry mortar fabrication. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2016.01.059

Salahuddin, H., Qureshi, L. A., Nawaz, A., & Raza, S. S. (2020). Effect of recycled fine aggregates on performance of Reactive Powder Concrete. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2020.118223

Santha Kumar, G. (2019). Influence of fluidity on mechanical and permeation performances of recycled aggregate mortar. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2019.04.093

Seo, D. S., & Choi, H. B. (2014). Effects of the old cement mortar attached to the recycled aggregate surface on the bond characteristics between aggregate and cement mortar. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2014.02.047

Silva, J., de Brito, J., & Veiga, R. (2010). Recycled red-clay ceramic construction and demolition waste for mortars production. *Journal of Materials in Civil Engineering*. https://doi.org/10.1061/(ASCE)0899-1561(2010)22:3(236)

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*. https://doi.org/10.1016/j.conbuildmat.2014.04.117

Silva, R. V., De Brito, J., & Dhir, R. K. (2016). Performance of cementitious renderings and masonry mortars containing recycled aggregates from construction and demolition wastes. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2015.12.171

Sim, J., & Park, C. (2011). Compressive strength and resistance to chloride ion penetration and carbonation of recycled aggregate concrete with varying amount of fly ash and fine recycled aggregate. *Waste Management*. https://doi.org/10.1016/j.wasman.2011.06.014

Tam, V. W. Y., & Le, K. N. (2008). On efficiency improvement of demolished concrete, recycled aggregate and recycled aggregate concrete testing. *Australian Journal of Civil Engineering*. https://doi.org/10.1080/14488353.2008.11463940

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*. https://doi.org/10.1016/j.cemconres.2004.10.025

Tam, V. W. Y., Gao, X. F., Tam, C. M., & Ng, K. M. (2009). Physio-chemical reactions in recycle aggregate concrete. *Journal of Hazardous Materials*. https://doi.org/10.1016/j.jhazmat.2008.07.031

Tam, V. W. Y., & Tam, C. M. (2007). Assessment of durability of recycled aggregate concrete produced by two-stage mixing approach. *Journal of Materials Science*. https://doi.org/10.1007/s10853-006-0379-y

Thomas, J. J., Jennings, H. M., & Chen, J. J. (2009). Influence of nucleation seeding on the hydration mechanisms of tricalcium silicate and cement. *Journal of Physical Chemistry C*. https://doi.org/10.1021/jp809811w

Vieira, T., Alves, A., de Brito, J., Correia, J. R., & Silva, R. V. (2016). Durability-related performance of concrete containing fine recycled aggregates from crushed bricks and sanitary ware. *Materials and Design*. https://doi.org/10.1016/j.matdes.2015.11.023

Xiao, J., Li, W., Fan, Y., & Huang, X. (2012). An overview of study on recycled aggregate concrete in China (1996–2011). *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2011.12.074

You, Z., Mills-Beale, J., Williams, R. C., & Dai, Q. (2009). Measuring the specific gravities of fine aggregates: An automated procedure. *International Journal of Pavement Research and Technology., 2*, 37.

Zega, C. J., & Di Maio, Á. A. (2011). Use of recycled fine aggregate in concretes with durable requirements. *Waste Management*. https://doi.org/10.1016/j.wasman.2011.06.011

Zeyad, A. M., Tayeh, B. A., Saba, A. M., & Johari, M. A. M. (2018). Workability, setting time and strength of high-strength concrete containing high volume of palm oil fuel ash. *The Open Civil Engineering Journal., 12*, 35–46. https://doi.org/10.2174/1874149501812010035

Zhang, K., & Xiao, J. (2018). Prediction model of carbonation depth for recycled aggregate concrete. *Cement and Concrete Composites*. https://doi.org/10.1016/j.cemconcomp.2018.01.013

Zhang, W., Zakaria, M., & Hama, Y. (2013). Influence of aggregate materials characteristics on the drying shrinkage properties of mortar and concrete. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2013.08.069

Zhao, Z., Remond, S., Damidot, D., & Xu, W. (2015). Influence of fine recycled concrete aggregates on the properties of mortars. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2015.02.037

Zhi Yuan, C., & Jian Guo, W. (1987). Bond between marble and cement paste. *Cement and Concrete Research*. https://doi.org/10.1016/0008-8846(87)90127-X

Zimbelmann, R. (1985). A contribution to the problem of cement-aggregate bond. *Cement and Concrete Research*. https://doi.org/10.1016/0008-8846(85)90146-2

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.