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Coconut shell waste as an alternative lightweight aggregate in concrete- A review

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Abstract. This review article highlights the physical, mechanical, and chemical properties of coconut shells, and the fresh and hardened properties of the coconut shell concrete are summarized and were compared with other types of aggregates. Furthermore, the structural behavior in terms of flexural, shear, and torsion was also highlighted, with other properties including shrinkage, elastic modulus, and permeability of the coconut shell concrete. Based on the reviewed literature, concrete containing coconut shell as coarse aggregate with normal sand as fine showed the 28-day compressive strength between 2 and 36 MPa with the dried density range of 1865 to 2300 kg/m^3. Coconut shell concretes showed a 28-day modulus of rupture and splitting tensile strength values in the ranges of 2.59 to 8.45 MPa and 0.8 to 3.70 MPa, respectively, and these values were in the range of 5-20% of the compressive strength. The flexural behavior of CSC was found similar to other types of lightweight concrete. There were no horizontal cracks on beams which indicate no bond failure. Whereas, the diagonal shear failure was prominent in beams with no shear reinforcements while flexural failure mode was seen in beams having shear reinforcement. Under torsion, CSC beams behave like conventional concrete. Finally, future recommendations are also suggested in this study to investigate the innovative lightweight aggregate concrete based on the environmental and financial design factors.

Keywords: chemical composition; coconut shell concrete; flexural and shear behavior; mechanical properties; torsion; permeability

1. Introduction

Structural concrete plays a most important role in the construction industry and has been widely used in all civil engineering structures (Hussein *et al.* 2012), because it can be molded into a variety of sizes and shapes and it also has the best resistance to water (Calkin 2009). Currently, the construction industry is annually consuming a huge amount of natural resources such as around 1 billion tons of water, 10-12 billion tons of stones as fine and coarse aggregates, and 1.5-2 billion tons of cement (Shafigh *et al.* 2013), and this huge consumption of raw materials causing depletion of natural resources around the world and also significantly affecting the environment

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(Altwair and Kabir 2010).

The overall production of concrete around the world is increasing day by day which causes significant damage to the environment (Silva *et al.* 2016). Furthermore, this depletion can be attained by considering the chemical composition of the materials utilized for concrete production, specifically, the composition of conventional cement (OPC). As high demand of concrete industry using the conventional crushed granite aggregates (NWAs) reducing the natural deposits and causing irreparable damage has emphasized the researchers to focus on sustainable development (Alengaram *et al.* 2013) to use or convert the waste or recycled materials as a potential concrete material (Mo *et al.* 2015).

In the concrete industry, lightweight concrete (LWC) is not an unused innovation, as it has been utilized since ancient times and is additionally considered as the foremost curious field of research. It has several advantages such as better frost, fire and heat resistance, good performance in seismic damping, better sound absorption, and best anti-condensation properties (Shafigh *et al.* 2010). The most used method for the production of LWC is by using the lightweight aggregate (LWA) (Polat *et al.* 2010) and the LWAs are normally classified in two sets such as artificial and natural. In further classification, the artificial aggregates are subdivided into two groups, namely, modified naturally available materials and industrial by-products. Natural modified materials that were prepared under high temperature and pressure are expanded clay, vermiculite, shale, slate and perlite, whereas, the industrial by-products used as the LWAs are sintered pulverized fuel-ash and slate, foamed or expanded blast furnace slag and the colliery waste. The main naturally available LWAs are scoria, diatomite, volcanic cinders, pumice, scoria and tuff (Neville and Brooks 2008, Shafigh *et al.* 2010).

The lightweight aggregates obtained from the industrial waste materials used for the production of LWC are bed ash, sintered pulverized fuel ash and expanded slag which promotes the use of sustainable development materials (Chandra and Berntsson 2002). Over a long period, the LWAs have been utilized in the concrete industry and proved to be cost-effective by providing both economic viability and structural stability (Emdadi *et al.* 2014), furthermore, the lighter structures are considered more versatile structures (Zhang and Poon 2015). Since last few decades, several types of manufactured and natural LWAs have been used as the alternative sustainable construction materials (CEB/FIP 1983, Mo *et al.* 2016).

The coconut shells are more likely cultivated in the tropical countries and islands such as Malaysia, Thailand, Philippines, Indonesia, Southeast Asia, and the continent as well. Furthermore, in the Indian Ocean, the cultivation hub for CS is southern areas of India, Maldives, Sri-Lanka, and the surroundings (Mo *et al.* 2020). Around the globe, 92 countries are producing the CSs on an area of more than 10 million hectares. India, Philippines, and Indonesia produce about 75% of the total coconut production with Indonesia being the world's leading producer. The coconut farm is a source of a variety of products such as it produces electricity, fiber boards, heat, animal feeds, organic fertilizers, health drinks and the fuel additives for the cleaner emissions (Salam *et al.* 1987, Gunasekaran *et al.* 2017, Ramasubramani and Gunasekaran 2021). The husk known as the coir of coconut has been used to prepare several products such as ropes, carpets, mattresses, door mats, brushes, car seat covers and the bristles etc., and this fibrous material is hard, tough, and is highly resistant to the sea water.

Although it was found that a variety of products have been made by coconut shells, in addition, it has also been used as an LWA for producing lightweight aggregate concrete. Therefore, this article aims to critically review the potential usage of CS as an LWA in the concrete mixture. The detailed exploration was performed to identify the chemical and physical properties of the CS

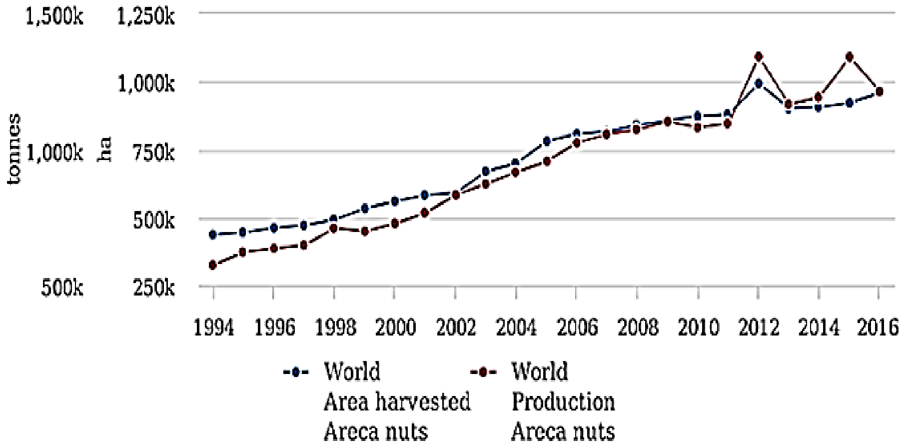

Fig. 1 Production/Yield quantities of Coconuts in World+(Total) (1994-2016)

aggregates and were also compared with other types of aggregates. Furthermore, the mechanical properties of the CSC mixes were also discussed and compared. Based on the reviewed literature, authors could believe that the significant attainments can be achieved by summarizing and analyzing the basic properties of CS. In addition, the new research area is also identified for the researchers to investigate the innovative LWC based on environmental and financial design aspects.

2. Origin of coconut shell

In general, mostly the coconut shells are found in tropical regime countries and have been commonly categorized as dwarf and tall varieties based on the shape and habit of the tree. Majority of the coconut trees are tall; however, dwarf trees are also available which are only a few feet tall at the time of reproduction. The production of dwarf trees is only about 5% of coconuts and that was normally used for the eating purpose, while the tall normally form the coconut oil and the fibers. The production quantities of coconut shells around the world from 1994 to 2016 are shown in Fig. 1.

3. Physical properties

This section thoroughly describes all the physical properties of the CS as a coarse aggregate (CA) including the specific gravity, sieve analysis, thickness, texture, bulk density and the water absorption.

3.1 Specific gravity

Mostly, the researchers have used the pycnometer test method (BS:1377) to obtain the specific gravity of the crushed coconut shell (CCS) and crushed granite aggregates. The specific gravity of CCS as fine aggregates was found about 2.29, and as coarse aggregate it showed on average about

2.29. The ASTM D-58 recommended that the specific gravity of good aggregates is normally found in the range of 2.2-2.6 (Otunyo *et al.* 2014). Anwar *et al.*, (2016) utilized the CS particles with the size of 20 mm-600µ as a reinforcing material and reported that the CS has a specific gravity of 1.33 and has high strength and modulus properties. Further, the maximum CS as coarse aggregate size was 12.5 mm and the fineness modulus of 7.0 showed the specific gravity of 1.15 (Yashida and Sujatha 2017).

CS as coarse aggregate was utilized to produce the concrete and the properties were investigated by Abirami *et al.* (2016), and the specific gravity was found in the range of 1.05-1.20. Normally, they showed the variety of shapes, sizes, colors, and weight, depending on the maturity and genetic variety of nut at the harvest. The CS as an aggregate with the particle sizes range from 5 to 20 mm showed a specific gravity of 1.5 (Subramani and Anbuvel 2016). Olanipekun *et al.* (2006) determined the physical properties such as water absorption, moisture content, durability and density of the CS and palm kernel shells (PKS) and reported the specific gravity of both shells of about 1.74. Furthermore, the coconut shell showed the specific gravity of 1.12 (Patel *et al.* 2015a). The CS was considered as an exceptional aggregate based on its properties and further, it has a specific gravity of 1.2 twice the density of hardwood (Tharwani *et al.* 2017). The water absorption of the CS was found about 8% and the specific gravity in SSD condition was found at around 1.3 (Rao *et al.* 2015). Specific gravity of CS is low as compared to NWA and it was found about 1.12 as reported by Patel *et al.* (2015b), and this value was also found about 1.33 (Mohapatra and Parhi 2017).

Rajasekhar *et al.* (2016) reported the specific gravity of CS is about 1.26, however, in another study, CS as coarse aggregate showed this value of about 1.467 and as a fine it was about 1.439 (Ramadhansyah *et al.* 2016). Later, the specific gravity of CS was also found about 1.56 (Kumar and Kumar 2012) and the apparent specific gravity and the average specific gravity were reported in the ranges of 1.40 to 1.50 and 1.05 to 1.20, respectively, and such values were lower than the specific gravity of the NWAs (Gunasekaran *et al.* 2017, Chandar *et al.* 2019). In general, it was found that the CS as a coarse aggregate showed the lowest values compared to all the other types of aggregates mentioned in Table 1. The specific gravity of CS was found about 26 to 56% lower than the PKS aggregate, about 28 to 41% lower than the oil-palm-boiler clinker (OPBC) aggregate, and about 43 to 62% lower than the NWAs. In addition, the crushed coconut shell (CCS) as fine aggregate showed about 13 to 60% lower specific gravity results compared to the conventional sand as fine aggregate.

3.2 Sieve analysis

The particle size distribution of the CS aggregates was determined by the sieve analysis, often referred to as the gradation of aggregates. Normally for concrete, the coconut shell utilized as an aggregate has the size of about 16 mm (Kumar *et al.* 2017), they were preparing as after crushing, were sieved and passed from a sieve of 12.5 mm size (Gunasekaran and Kumar 2008). It was reported that the CS aggregates are a potential substitute to develop the new composites because of their higher modulus and the strength (Kambli and Mathapati 2014). The maximum size of coconut shell particles was selected as 12.5 mm by the number of researchers (Gunasekaran *et al.* 2011, Kambli and Mathapati 2014, Leman *et al.* 2017, Abirami *et al.* 2016, Shinde *et al.* 2016). Kamal *et al.* (2015) investigated the coconut shell concrete by considering the particle size in the range of 10 to 20 mm after the crushed materials were washed and allowed to dry under normal laboratory conditions for 1 month. Whereas, in other studies, the particle size of the coconut shell

Table 1 Comparison of physical properties of CS aggregates with other type of aggregates

Physical Properties	Coarse Aggregates				Fine Aggregates	
	NWA	Coconut shell	OPS / PKS	OPBS	Sand	CCS
Specific gravity	2.6-2.8	1.0-1.6	2.17	1.7-2.2	2.5-2.65	1.0-2.3
Fineness modulus	4.2-7.5	6.2-6.8	-	-	2.2-3.3	14.2
Bulk density (kg/m^3)	1367-1790	510-800	864	740-1120	1530-1760	1428
Moisture content (%)	-	4.2-4.3	0.08	0.07-1	1.4-7.9	16.7
Water absorption (%)	0.5-1.8	6.0-29.3	8.15	2-26.4	0.8-1.1	-
References	(Afolayan *et al.* 2017, Anwar *et al.* 2016, Kumar *et al.* 2016, Reddy *et al.* 2017, Yashida and Sujatha 2017)	(Abirami *et al.* 2016, Afolayan *et al.* 2017, Anwar *et al.* 2016, Chakravarthy *et al.* 2017, Gunasekaran *et al.* 2011, 2017, Kumar and Kumar 2012, Mohapatra and Parhi 2017, Patel *et al.* 2015a, 2015b, Rajasekhar and Spandana 2016, Ramadhansyah *et al.* 2016, Subramani and Anbuvel 2016, Yashida and Sujatha 2017)	(Alengaram *et al.* 2013, Salam *et al.* 1987, Shafigh *et al.* 2010, 2013)	(Aslam *et al.* 2015, 2016a, 2016b, Aslam *et al.* 2016, 2017a; 2017b, Hussein *et al.* 2012)	(Abirami *et al.* 2016, Anwar *et al.* 2016, Otunyo *et al.* 2014, Subramani and Anbuvel 2016, Yashida and Sujatha 2017, Chandar *et al.* 2018)	

was set in the range of 5 to 20 mm (Aminah and Sabarudin 2009), its size ranges between 5 and 15 mm (Olanipekun *et al.* 2006), and the particle sizes ranging from 12 to 20 mm with the surface texture of rough on convex and fairly smooth on concave faces (Kumar *et al.* 2017). Patel *et al.* (2015b) investigated the coconut shell concrete by considering 10% CS of 8 mm size and 10% of 10 mm size and 10% of 12.5 mm. Two broken pieces of coconut shells were collected and air-dried at the temperature of 25 to 30ºC for five days; after removing the husk and fibers from dried shells were further crushed and sieved with the sieve size of 12.5mm. The material passed from the sieve size of 12.5 mm sieve was utilized in the investigation and the remaining material was discarded (Rao *et al.* 2015). The maximum size of 20 mm CS was used by (Mohapatra and Parhi 2017) and the angular shaped 20 mm was utilized by (Shaikh *et al.* 2015), however, the partial replacement of NWAs with CS aggregates at the level of 25% and 30% of the size 15 mm was utilized by Reddy *et al.* (2017).

Rajasekhar and Spandana (2016) reported the maximum size of CS as 20 mm, and after crushing the size of 12.5 mm was reported by Amutha *et al.* (2015), Kumar *et al.* (2016). Furthermore, the maximum thickness of CS particles of about 2 mm and aggregates sizes in the range of 6-20 mm have been utilized (Pavani and Ramarao 2016), and 5-20 mm have been considered by Sonawane and Chitte (2016). Miron (2015) prepared the asphaltic concrete by utilizing CS as coarse aggregate with the nominal size of 14 mm and the maximum size of CS was 20 mm used by Harle (2017) and Kumar and Kumar (2012). The outer pericarp of the shells

Fig. 2 Coconut shell as coarse aggregate (CSA) after crushing (Afolayan *et al.* 2017)

known as Cocos nucifera were collected and sieved with 2 mm mesh pore size (Ewansiha *et al.* 2012). For the specification, four consecutive sieves sizes such as 355 μm, 180 μm, 125 μm, and 63 μm were used for the size fractions (Madakson *et al.* 2012). Leman *et al.* (2016) investigated the CS powder as a filler in the concrete. The shells were collected from the local industry, before the preparation, it was sun-dried and crushed into small pieces and later was ground into the powder, then the final product was sieved from 63μ sieve. The fineness modulus of CS as a coarse aggregate was generally found in the range of 6.2 to 6.8, which is normally found in the range of fineness modulus of conventional coarse aggregates as can be seen in Table 1.

3.3 Thickness, texture and bulk density

The CS particles are used as a reinforcing material in the concrete, it also has higher strength and modulus properties. Kumar *et al.* (2012) reported the shell thickness in the range 3-6 mm, however, in another study (Anwar *et al.* 2016) it was found in the range of 2-7 mm. The coconut shells are normally available in various shapes such as flaky, curves, roughly parabolic, elongated, and irregular shapes as can be seen in Fig. 2, and its surface texture is slightly rough on convex and fairly smooth on the concave faces (Afolayan *et al.* 2017).

The bulk density of CSA is about 630 kg/m^3 (Afolayan *et al.* 2017). Gunasekaran *et al.* (2008) reported the loose bulk density and compacted bulk density of about 550 kg/m^3 and 650 kg/m^3. Some other studies reported bulk density between 500 and 600 kg/m^3 for CSA and it is suitable for producing the LWC (Chakravarthy *et al.* 2017) and the bulk density of CS was reported of about 650 kg/m^3 (Gunasekaran *et al.* 2011, Leman *et al.* 2017, Patel *et al.* 2015a, Yashida and Sujatha 2017). Anwar *et al.* (2016) reported the loose bulk density of 590 kg/m^3 and the compacted density of 800 kg/m^3 for the coconut shell aggregates. Several researchers (Kumar and Kumar 2012, Mohapatra and Parhi 2017, Shinde *et al.* 2016, Subramani and Anbuvel 2016) utilized the CSAs and reported the bulk density range of 510 to 600 kg/m^3. Otunyo (2014) utilized the crushed coconut shell as a fine aggregate and reported the bulk density of about 1428 kg/m^3 which was about 19% lower than the mining sand. Generally, it was found that the CS as coarse aggregate showed about 55% lower bulk density compared to normal weight aggregates, and it is about 7%, and 23% lighter than the PKS and OPBC aggregates, respectively as shown in Table 1.

3.4 Water absorption

The comparison of the water absorption and the moisture content of the CSA with other types of materials is shown in Table 1. The CS aggregate showed the water absorption of about 8% and having the shape of two-dimensional particles, and the lateral dimension to thickness is nearly 15 for 12 mm CS particles (Yerramala and Ramachandrudu 2015). Gunasekaran (2008) reported the moisture content and the water absorption of CSAs as 4.2% and 24%, respectively. However, the majority of studies (Abirami *et al.* 2016, Gunasekaran *et al.* 2017, Gunasekaran *et al.* 2011, Kumar *et al.* 2016, Leman *et al.* 2017, Ramadhansyah *et al.* 2016, Vinod *et al.* 2017) revealed that the 24-hour water absorption of crushed CS is about 24%, and this value was found about 25% by Anwar *et al.* (2016). Ganiron *et al.* (2013) reported that the coconut hollow block showed a water absorption of 4% and coconut hollow block and fibers have normally a water absorption of 2.63%. Some studies (Shinde *et al.* 2016, Subramani and Anbuvel 2016) also reported the water absorption of the CS of about 23%. A comparative study for the water absorption of conventional and coconut shell aggregates was performed. It was observed that the conventional aggregate showed an absorption value of 1% and the CS value was about 9.6%. Since the coconut shell is a wood base material its water absorption is more as compared to NWA (Deshmukh *et al.* 2016).

Kamal and Singh (2015) studied the strength characteristics by the partial replacement of NWAs with the CS aggregates. The incorporation of 30% CS aggregates showed 2.1% water absorption of the concrete mixes after 30 minutes. The CS aggregates showed a water absorption of about 6.17%, while, for PKS aggregate it was about 8.15% (Olanipekun *et al.* 2006). It was reported that the CS aggregate showed higher water absorption due to higher porosity in the shell structure (Kukarni and Gaikwad, 2013). The water absorption of the CS was found about 24.03% (Patel *et al.* 2015a; 2015b), in another study, it was about 4.5% (Rao *et al.* 2015), 7.6% was reported by Mohapatra and Parhi (2017), 26.05% was found in De-Costa *et al.* (2014), 6% reported in (Rajasekhar and Spandana 2016) and it was also found about 8% with the specific gravity of 1.33 (Nurfatin *et al.* 2016). Water absorption of CSAs compared to the other types of aggregates is shown in Table 1. It was found that CS aggregate showed the highest water absorption values compared to the other types which were about 94% higher than NWAs, 72% higher than PKS, and about 10% higher than the OPBC aggregates.

4. Chemical composition of coconut shell

Normally, the LWC showed lower permeability because it is expected the LWA and the cement paste have a better contact zone compared to the conventional NWC. The improvement in the contact zone is mainly due to the vesicular nature of aggregate and the internal curing of the aggregates, which develops the suction pressure to seep the paste into the pores of the particle to improve the bond performance, furthermore, the bond between paste and aggregates depends on the pozzolanic nature of the particles (Technology 1983, Bremner and Holm 1995).

Recently, the reduction in pores and water absorption of CSC was explored by Thilagashanthi *et al.* (2022). Firstly, the CS aggregates were treated using sago flour and slaked lime. It was found that the treated CS aggregates significantly reduce the pores in the concrete due to that the water absorption of the CSC mixture was also reduced. In coconut shells, the percentage composition of carbon, hydrogen, nitrogen, Sulphur and oxygen values are 49.62,7.31,0.22,0.10, and 42.75, respectively (Iqbaldin *et al.* 2013). Whereas, the coconut residual solid percentage composition of

Table 2 Chemical composition of coconut shell and other types of aggregates

Elements		CS	OPBC	Pumice	LECA	Lytag	OPS/PKS
Calcium oxide	CaO	0.57	2.3-8.2	1.0-2.0	2.0-2.5	3.0-4.0	20.27
Silica dioxide	SiO_2	45.05	59.6-81.8	60-75	62-66	50-53	31.73
Ferric oxide	Fe_2O_3	12.4	4.62-5.2	1.0-7.0	7.0-9.0	5.0-6.0	1.78
Sulphur trioxide	SO_3	-	0.73	0.14	1.0-16.0	0.3	-
Aluminium oxide	Al_2O_3	15.6	3.5-3.7	13-17	0.2-16.0	23-25	3.46
Magnesium oxide	MgO	16.2	1.2-5.0	1.0-2.0	1.0-4.0	2.8-3.0	1.01
Phosphorous pentoxide	P_2O_5	-	0.8-5.3	-	0.21	-	2.57
Potassium oxide	K_2O	0.52	4.6-11.6	7.0-8.0	2.0-3.5	0.2	1.51
Titanium dioxide	TiO_2	-	0.2	-	-	-	12.39
Natrium oxide	Na_2O	0.45	0.1-0.3	3.0-5.0	0.7-2.0	0.3	1.38
Manganese trioxide	Mn_2O_3	-	-	-	-	-	-
Manganese oxide	MnO	0.22	-	-	0.14	-	1.27
Ash	-	3.38	-	-	-	-	-
Nitrogen	N	0.2-0.4	-	-	-	-	-
Sulphur	S	0.1-0.17	-	-	-	-	-
Chloride	Cl	0.95	-	-	-	-	0.08
Carbon	C	49.6-63.4	-	-	-	-	12.55
Oxygen	O	28.3-42.8	-	-	-	-	-
Hydrogen	H	6.7-7.3	-	-	-	-	-
References		(Aslam *et al.* 2016b, 2018, Iqbaldin *et al.* 2013, Arioz and Karasu 2008, Hemmings *et al.* 2009, Hossain and Khandaker 2004, Shafigh *et al.* 2010, 2013, Ting *et al.* 2016, Tsai *et al.* 2006)					

carbon, hydrogen, nitrogen and oxygen were 69.33,3.26,0.94, and 15.29, respectively and in the liquid, the composition of carbon, hydrogen, nitrogen and oxygen values were 10.29,7.01,0.27, and 43.22, respectively (Tsai *et al.* 2006). The chemical composition of CS aggregates and the other types of LWAs is provided in Table 2. It can be seen that the CS aggregate has an almost similar chemical composition to the OPBC and other natural LWAs such as pumice and the artificial LWAs such as Lytag and expanded clay aggregate (LECA). Compare to these LWAs, OPS / PKS has many diverse chemical properties as an unstable agricultural waste. In this manner, it can be said that at higher temperatures the CSC have better performance compared to the PKSC.

5. Mechanical and durability properties of CS aggregates

Mechanical properties of CSA i.e., LA abrasion test, crushing and impact values were reported by several researchers. The lowest abrasion value for the CS aggregate was found about 1.63% (Gunasekaran *et al.* 2011, Leman *et al.* 2017), whereas, in some studies, it was around 2.1%

(Magrey *et al.* 2016, Ramadhansyah *et al.* 2016) and 2.23% (Afolayan *et al.* 2017). Ghosal and Moulik 2015 reported that CSA have better resistance against abrasion, crushing and impact in comparison to NWA. In another study (De-Costa *et al.* 2014), it was found that CS has high toughness and abrasion-resistant properties. Similar to crushing and impact resistances, wear resistance also plays a major role for the aggregates. Commonly, the LWAs have lower abrasion resistance compared to that of NWA, because the LWAs are less stiff (Alengaram *et al.* 2013). The standards and codes recommended that the abrasion value should be less than 30% for the wearing surfaces, and should be less than 50% for all structural applications except the wearing surface (Neville and Brook 2008).

The toughness of aggregates normally refers to the resistance of the material to the impact failure. IS 283-1970 specified that the aggregates should have an impact value less than 45% by weight used for the structures, however, in concrete for wearing courses/surfaces it should be less than 30% by weight (Mehta and Monteiro 2006, Neville and Brook 2008). The impact value of CS was reported at about 1.30% (Afolayan *et al.* 2017). Impact value of CSAs was found significantly lower compared to NWAs which shows that it has good absorbance to the shock/waves (Ghosal and Moulik 2015, Gunasekaran and Kumar 2008). Generally, coconut shells show a good impact resistance (Kumar *et al.* 2017, Sekar and Gunasekaran 2018), its impact values vary in the range of 1.22% to 15.7% (Gunasekaran *et al.* 2011, Leman *et al.* 2017, Otunyo *et al.* 2014, Shinde *et al.* 2016).

It was found out that aggregate impact value was found to be very less of coconut shell aggregates compare to conventional aggregate (Deshmukh *et al.* 2016, Kanojia and Jain 2015, Subramani and Anbuvel 2016), which also shows its better shock absorbance (De-Costa *et al.* 2014, Mohapatra and Parhi 2017). Furthermore, the action to break the aggregate to a degree is relying on the impact resistance of that material. CS has more strength, based on its impact value of 5.7% and has low impact effect compared to NWAs, which also justifies that the CS aggregate has better ability to resist the sudden impact or shock (Kumar and Kumar 2012, Nurfatin *et al.* 2016, Sonawane and Chitte 2016). The resistance of material/aggregate to the crushing is normally measured by the crushing value under a gradual compressive load. The crushing value permitted for the structural components might be allowed up to 45%, however, for pavements and roads, it is resisted up to 30% (Mehta and Monteiro 2006). The crushing value for CS aggregates was found in the range of 1.16 to 21.84% (Afolayan *et al.* 2017, Gunasekaran and Kumar 2008, Gunasekaran *et al.* 2011, Kanojia and Jain 2015, Kumar and Kumar 2012, Leman *et al.* 2017, Magrey *et al.* 2016, Otunyo *et al.* 2014, Nurfatin *et al.* 2016, Shinde *et al.* 2016, Subramani and Anbuvel 2016) and were lower than NWAs, therefore, can be utilized for all the structural members.

Gunasekaran *et al.* (2015) suggested that depending upon the curing conditions a 10.66-11% water absorption was found at 28-days for CSAC and it decreases as the age increases. For CSAC, the volume of permeable voids (VPV) was found between 20.4 and 22.4% depending on the curing conditions and with age increase, VPV values decrease. Under full water curing, sorptivity for CSAC was about 0.095-0.104 mm/min$^{0.5}$ at 28 days. For CSAC, the rapid chloride penetration test (RCPT) at 28 days ranged between 2,765-3,880 C. For OPS concrete at 28-days of age, RCPT ranged from about 3,581 to 4,549 C (Teo *et al.* 2010). The RCPT values of LWC made from expanded clay ranged from 2,115-3,336 C (Chia and Zhang 2002). Gunasekaran *et al.* (2017) investigated the CSC using quarry dust (QD) as fine aggregate and this concrete showed higher density and lesser workability. Flexural strength and splitting tensile strength of CSCQ are 16.4% and 10.01% of compressive strength. For CCQ, flexural strength was about 16% of compressive strength and is increased by 2% in comparison to NWC.

Chandar *et al.* (2002) concluded that the durability properties of both CSC and NWC increased by using quarry dust in place of river sand. From 3 days to up to 365 days, the volume of permeable voids capacities reduced from 22.96 to 16.34% and 23.55 to 16.62% for CSC and CSCQ mix. The reduction in values shows the improvement in concrete durability behavior. Yadav and Gunasekaran (2019) studied the effect of OPC partial replacement with granite powder (GP) in CSC and NWC on mechanical properties of concrete. Compressive strength at 28 days of age increased to 10% GP value. The optimum dosage of GP was found to be 10% to achieve better mechanical properties for CSC and CC. For CSC, flexure strength and split tensile strength at 28 days were 10.80% and 7.38% of its 30.10 N/mm^2 compressive strength. The split tensile strength and flexure strength for CC at 28 days was 8.34% and 14.38% of its 31.30 N/mm^2 compressive strength.

Sekar and Gunasekaran (2019) reported that the CSC showed better durability performance compared to NWC with 2-hour temperature resistance therefore it can be preferred in the construction industry. Patel *et al.* (2019) used crushed granular coconut shells in place of conventional coarse aggregate to investigate the concrete strength properties. It was evident from the results that the compressive strength decreased with the increase in the dosage of coconut shells. The reduction in compressive strength was 8.30% and 8.96% at 5% and 10% partial replacement of coarse aggregates with coconut shells, respectively. It was concluded that to produce lightweight structural concrete coconut shells can be used in place of coarse aggregate.

Adebakin *et al.* (2019) studied the development of self-compacting lightweight concrete using 15% (SCCSC1) and 20% (SCCSC2) fly ash (FA) in place of ordinary Portland cement and coconut shells as coarse aggregate. For 15% FA, splitting tensile, compressive, and flexural strengths of 2.56 N/mm^2, 21.20 N/mm^2 and 4.50 N/mm^2 were achieved. Similarly, for 20% FA, 2.52 N/mm^2, 20.10 N/mm^2 and 4.00 N/mm^2 were achieved. It was concluded that self-compacting coconut shell lightweight concrete can be produced by using coconut shells. Adebakin *et al.* (2006) investigated the performance of self-compacting coconut shell concrete (SCCSC) using concrete shells as coarse aggregates and fly ash (FA) in 15% and 20% replacement ratios in place of ordinary Portland cement. The results for durability and mechanical properties compare well with different lightweight concretes. It was concluded that coconut shells can be used as an alternate aggerate for the development of self-compacting coconut shell lightweight concrete.

Prakash *et al.* (2020) used coconut shells in place of coarse aggregate to develop lightweight concrete and sisal fibers at 1%, 2%, 3% and 4% contents based on cement weight were used to enhance the weak mechanical properties of developed lightweight concrete. At 3% sisal fiber dosage flexural strength, compressive strength, modulus of elasticity and split tensile strength increased by up to 11%, 6%, 6% and 14%, respectively. Therefore, for the construction industry the use of sisal fiber with concrete shell concrete is considered as an eco-friendly and suitable constructional material alternative.

Kumar *et al.* (2018) studied the effect on mechanical properties of coconut shell concrete at 5%, 10% and 15% silica flume replacement ratios with cement. With the increase in coconut shells replacement with coarse aggregate, the density of developed coconut shell concrete decreased. For 10% silica flume replacement the compressive, flexural, and split tensile strength values were improved by 10.5%, 12.8% and 10.7% than controlled concrete. Thus, the optimum dosage of 10% silica flume replacement in place of cement was concluded for compressive, flexural, and split tensile strength.

Gunasekaran *et al.* (2021) and Pennarasi *et al.* (2019) investigated the durability and shrinkage properties of coconut shell concrete (CSC) hollow blocks prepared in the laboratory and field. The

Table 3 Selected Mix proportions of the lightweight aggregate concrete made of coconut shell as coarse aggregate

Mix design and Specimens details	Concrete							Aggregates		28-day Flexural and Tensile Strengths (MPa)		References
	w/c ratio	Mix Proportions	Type	Slump (mm)	Hardened Density (kg/m³)	Strength (MPa) 7 days	Strength (MPa) 28 days	Size (mm)	Type	Flexural	Splitting	
M1	0.6	Control Mix (NWA)	300	25	2365	11.11	22.33	19	Coarse	-	2.39	(Yerramala and Ramachandudu 2015)
M2		NWA+CS= 90%+10%	300	23	2186	5.16	13.56				1.51	
M3		NWA+CS= 85%+15%	300	22	2117	7.29	12.56				1.35	
M4		NWA+CS= 80%+20%	300	20	2061	7.82	9.33				1.15	
M5		NWA+CS= 80%+20%	225+F.A (75)=300	23	2027	3.47	7.22				0.8	
M6		NWA+CS= 80%+20%	204+F.A (96)=300	26	2023	5.56	9.67				1.08	
Control	0.40	Control Mix (NWC)	13.67 kg	60.5	2359	40.0	46.7	12.5	Coarse	-	-	(Leman *et al.* 2017)
5% CS		95% NWA+5% CS	13.67 kg	50.5	2326	16.1	29.6					
10% CS		90% NWA+10% CS	13.67 kg	25.0	2110	6.8	7.4					
M1	0.72	1:3.27:1.34	300 400 425 450 480 480 480 480 480 480 510	10	1865	-	04.95	12.5	Coarse	4.68 4.26	2.70 2.38	(Gunasekaran *et al.* 2011)
M2	0.55	1:2.05:0.84		25	1890		09.81					
M3	0.50	1:1.93:0.79		15	1910		13.24					
M4	0.45	1:1.83:0.75		25	1960		13.49					
M5	0.51	1:1.37:0.75		110	1900		10.30					
M6	0.42	1:1.67:0.69		65	1990		15.20					
M7	0.42	1:1.52:0.75		50	1950		16.19					
M8	0.44	1:1.60:0.80		50	1910		16.68					
M9	0.42	1:1.60:0.80		05	1930		17.66					
M10	0.42	1:1.60:0.70		30	1980		18.15					
M11	0.42	1:1.47:0.65		05	1970		26.70					
CS1	0.38	1:1.82:0.55		00	2060		23.40					
CS2	0.42	1:1.74:0.55		05	2040		16.72					
CS3	0.48	1:1.57:0.55		140	1960		13.38					
CS4	0.38	1:1.70:0.60		00	2010		19.50					
CS5	0.42	1:1.60:0.60		00	1990		16.16					
CS6	0.48	1:1.44:0.60		40	1980		13.38					
CS7	0.38	1:1.58:0.65		00	1985		27.20					
CS8	0.42	1:1.47:0.65		05	1970		26.70					
CS9	0.48	1:1.32:0.65		150	1920		14.50					
CSC	0.42	1:163:0.81	-	55	1930	14.9	19.1	12-15	Coarse	-	-	(Gunasekaran and Kumar 2008)

Table 3 Continued

Mix design and Specimens details	Concrete							Aggregates		28-day Flexural and Tensile Strengths (MPa)		References
	w/c ratio	Mix Proportions	Type	Slump (mm)	Hardened Density (kg/m^3)	Strength (MPa) 7 days	Strength (MPa) 28 days	Size (mm)	Type	Flexural	Splitting	
0% SF	-	-	-	5	1976	-	25.83	6.26 FM	Coarse	4.67	2.65	(Chakravarthy *et al.* 2017)
0.5% SF				5	1982		-			-	-	
1% SF				5	2039		-			-	-	
1.5% SF				5	2087		29.12			5.87	3.07	
2% SF				8	2127		-			-	-	
NWC	0.45	1:2:4	383	-	-	18.0	26.0	12.5	Coarse	3.17	2.82	(Abirami *et al.* 2016)
5% CS						17.8	25.1			2.36	2.63	
15% CS						16.5	24.5			2.91	2.58	
25% CS						16.46	21.7			3.36	2.50	
PC	0.45	1:1.5:3	440	52	-	19.11	27.33	12-20	Coarse	8.1	-	(Magrey *et al.* 2016)
C10				40		20.22	28.88			8.4		
C20				25		18.35	26.22			8.2		
C30				16		17.42	24.53			7.85		
F10				55		26.00	38.00			9.2		
F20				63		26.44	37.33			8.25		
F30				75		25.68	36.80			7.4		
C10 F10				47		14.88	30.22			8.45		
C10 F20				51		16.88	33.55			8.05		
C10 F30				67		25.00	35.55			7.8		
C20 F10				31		23.20	27.11			8.55		
C20 F20				39		18.57	29.33			8.35		
C20 F30				51		19.20	26.66			8.1		
C30 F10				20		21.25	24.44			8.45		
C30 F20				27		20.44	26.66			8.2		
C30 F30				38		19.68	27.77			7.85		
CC	-	NWAs	-	-	2358	15.29	20.3	5-20	Coarse	-	2.39	(Subramani and Anbuvel 2016)
5% CS		NWA+5% CS			2276	14.72	19.6				2.12	
10% CS		NWA+10% CS			2247	14.38	18.84				1.86	
15% CS		NWA+15% CS			2191	14.24	18.62				1.24	
20% CS		NWA+20% CS			1996	14.14	18.46				0.8	
CC	-	NWAs	-	84	-	29.78	36.44	5-20	Coarse	4.44	-	(Sathiskumar and Kumar 2017)
2.5% CS		NWA+2.5% CS		63		28.85	36			4.15		
5.0% CS		NWA+5% CS		68		28	35.11			3.85		
7.5% CS		NWA+7.5% CS		73		27.56	34.67			3.7		
10% CS		NWA+10% CS		80		26.67	34.22			3.63		
CC	0.44	1:1.48:2.99	-	40	2408	25.77	34.1	20	Coarse	7.95	3.42	(Kamal and Singh 2015)
10% CS				30	2384	19.29	28.53			6.85	3.04	
20% CS				34	2318	15.86	22.32			6.4	2.80	
30% CS				42	2240	12.22	20.12			5.9	2.33	
CC	0.44	2.01:4.162:4.62 (C:S:CA) 2.01:4.162:4.49:0.133 (C:S:CA:CS)	-	28	-	13.3	20.3	20	Coarse	-	-	(Jeyapriya and Kamalnatraj 2017)
10% CS				18		13.8	22.3					
20% CS				25		14.3	22.9					
30% CS				28		16.2	23.8					

Table 3 Continued

Mix design and Specimens details	Concrete							Aggregates		28-day Flexural and Tensile Strengths (MPa)		References
	w/c ratio	Mix Proportions	Type	Slump (mm)	Hardened Density (kg/m^3)	Strength (MPa) 7 days	Strength (MPa) 28 days	Size (mm)	Type	Flexural	Splitting	
Normal mix	0.5	0% CS	425	-	-	28.45	31.6	12-20	Coarse	-	-	(Kumar *et al.* 2017)
Mix1		5% CS				16.7	18.9					
Mix 2		10% CS				13.54	15.49					
Mix 3		15% CS				9.89	15.93					
Mix 4		5% CS				20.19	21.28					
Mix 5		10% CS				16.75	17.96					
Mix 6		15% CS				14.48	16.7					
Mix 7		5% CS				21.9	22.42					
Mix 8		10% CS				17.53	18.6					
Mix 9		15% CS				15.51	16.7					
NWC	-	Conventional	-	72	-	20.53	27.58	4.75-20	Coarse	3.91	2.88	(Patel *et al.* 2015b)
Mix 1		10% CS		66		18.14	23.46			3.58	2.71	
Mix 2		20% CS		60		16.83	20.95			3.20	2.06	
Mix 3		30% CS		52		15.63	18.94			2.9	1.85	
Mix 4		40% CS		46		13.51	17.06			2.57	1.59	
Mix 5		50% CS		37		11.05	15.48			2.10	1.26	
M1 0% CS	0.43	Cement: Coconut:	41.38 kg	-	2365	23.4	37.3	20	Coarse	-	3.7	(Rao *et al.* 2015)
M2 10% CS	0.51	Fine: Coarse	41.38 kg		2186	24.2	38.1				3.6	
M3 20% CS	0.45	191.61: 425.8:	41.38 kg		2061	23.9	37.1				3.7	
M4 30% CS	0.43	517.99: 1180.36	37.24 kg		2027	26.67	36.7				3.6	
M5 10% CS+20% FA	0.43	0.45:1:1.21:2.77	33.10 kg		2023	27.43	37.0				3.5	
TM1	0.45	0% CS	372	38	-	22.22	32.08	20	Coarse	-	3.26	(Mohapatra and Parhi 2017)
TM2		5% CS		35		21.46	31.56				3.34	
TM3		10% CS		33		21.68	30.84				3.06	
TM4		15% CS		32		20.79	29.56				2.99	
TM5		20% CS		30		19.88	28.67				2.76	
TM6		5% CS		38		20.67	31.33				2.70	
TM7		10% CS		31		17.22	28.00				2.38	
TM8		15% CS		29		16.04	24.89				2.27	
TM9		20% CS		27		15.45	22.00				2.19	
M1	0.5	10% CS	394	62	2370	16.8	24,2	10	Coarse	-	-	(Harle 2017)
M2		20% CS		65	2270	12.5	23.4					
M3		30% CS		79	2255	10.1	2.3					
M4		40% CS		83	2140	9.2	16.7					

Table 3 Continued

Mix design and Specimens details	Concrete							Aggregates		28-day Flexural and Tensile Strengths (MPa)		References
	w/c ratio	Mix Proportions	Type	Slump (mm)	Hardened Density (kg/m^3)	Strength (MPa) 7 days	Strength (MPa) 28 days	Size (mm)	Type	Flexural	Splitting	
Mix1 Mix 2 Mix 3 Mix 4 Mix 5 Mix 6 Mix 7 Mix 8 Mix 9 Mix 10 Mix 11 Mix 12	0.5	0% CS 5% CS 10% CS 10% CS 15% CS 20% CS 20% CS 20% CS 25% CS 25% CS 30% CS 35% CS	383.00 384.17 385.76 386.55 387.34 388.13 388.92 3.89.71 390.50 391.29 391.29 390.50	50-100	-	18.01 17.90 16.80 16.89 16.89 17.70 12.90 14.78 15.00 11.95 12.79 11.23 11.06	20.49 24.12 20.77 20.77 24.61 20.83 20.83 20.86	19	Coarse	3.17 2.283 2.535 2.535 2.89 2.60 2.60 2.42	3.82 2.45 1.94 1.94 2.57 1.98 1.98 2.45 0.97 0.66	(Reddy *et al.* 2017)
Control Mix CS-15-SF0% CS15-SF10% CS15-SF15% CS-30-SF0% CS30-SF10% CS30-SF15% CS-45-SF0% CS45-SF10% CS45-SF15%	0.55	Conventional Mix 15% CS and 0% Silica Fume 15% CS and 10% Silica Fume 15% CS and 15% Silica Fume 30% CS and 0% Silica Fume 30% CS and 10% Silica Fume 30% CS and 15% Silica Fume 45% CS and 0% Silica Fume 45% CS and 10% Silica Fume 45% CS and 15% Silica Fume	350	-	2421 2315 2231 2136	21.24 19.41 23.64 24.15 16.81 19.44 20.26 14.97 18.33 18.9	30.74 26.29 32.78 34.04 22.89 28.57 29.71 18.81 18.33 18.92	4.75-20	Coarse	7.11 4.88 5.93 6.21 4.12 4.92 5.58 3.78 4.54 5.01	3.09 2.47 2.87 2.98 2.38 2.47 2.64 2.05 2.29 2.41	(Pavani and Ramarao 2016)

F.A.=Fly Ash, CS=Coconut shell, SF=Silica Fume

addition of CSA causes a reduction in shrinkage cracks compared to conventional concrete (CC). CSC hollow block mixes if vibrated in the laboratory can enhance the durability properties. The allowable limit of 20% water absorption was justified by hollow blocks. Therefore, the CS can be used in the production of hollow blocks.

Prakash *et al.* (2020) examined the effect of polypropylene fiber addition on the mechanical properties of concrete made with CSA and fly ash (FA) as partial cement replacement. The density and slump were reduced with the polypropylene fiber addition. The modulus of elasticity and compressive strength increased up to 0.5% of polypropylene fiber volume fraction and reduced with further increase in fiber volume fraction.

6. Mix proportions and workability for CS concrete

In well-designed concrete mixes, the quantity of binder and its affiliation with strength is fairly constant for a specific type or among one and another type. For that purpose, the researchers always prefer different trial mixes with varying cement contents, CS as coarse and fine aggregates as well as the conventional NWAs to achieve the desired values for the compressive strengths. Based on a thorough literature review, the selected mix proportions made of CS concrete, and their fresh and hardened properties are shown in Table 3. Several design trials were prepared by the researchers using different binders, CSAs as sand and NWA replacement for the production of structural LWAC. Yerramala and Ramachandrudu (2015) investigated the comparative behavior of normal-, and lightweight concretes using the conventional and CS aggregates. They prepared six mixes in which the mix M1 was controlled NWC with 0% CS, M2 contains 10% CS, M3 got 15% CS incorporation, M4 contains 20% CS aggregates and finally, the mix M5 contains both CS and fly ash with the percentages of 20 and 25%, respectively, whereas, the M6 mix contains 20% CS and 5% of fly ash. They reported the slump values in the range of 20-26 mm, although the incorporation of CS in the conventional concrete has no significant effect on the workability of the concrete.

Leman *et al.* (2017) studied the workability and the compressive strength of the coconut shell aggregate concretes. They prepared three mixes with the same water to binder ratio of 0.4, first was control NWC and in the second mixture, the replacement of conventional aggregates was 5%, whereas, in the third mixture, the CS incorporation was 10% in the control concrete. The slump values were found in the range of 25 to 61 mm, it was observed that the contribution of CS in the conventional concrete has significantly reduced the workability of the mixture, even the incorporation of 10% CS showed about 59% lower workability compared to the control conventional aggregate concrete.

Gunasekaran *et al.* (2011) investigated the mechanical and bond properties of the CSC by utilizing locally available CS aggregate. They prepared two sets of concretes containing 20 mixes, in the first set the *w/b* ratio was utilized in the range of 0.42 to 0.72, and the mix proportioning ratios were also varying as shown in Table 3. However, in set 2 mixes the w/b ratio was reduced in the range of 0.38 to 0.48, and the mix proportioning ratio were also varying. The first set showed a huge difference between the slump values as they were ranging between 5 and 110 mm, however, in set 2, most of the mixes showed slump values in the range of 0 to 5 mm, only two mixes showed values of 140 mm and 150 mm. Gunasekaran and Kumar (2008) prepared one mix of lightweight concrete using the coconut shell aggregate. They considered the w/b ratio of 0.42 and the mix proportioning ratio of 1:163:0.81, and the mixture showed the slump value of about 55 mm and dried density 1930 kg/m^3. Chakravarthy *et al.* (2017) performed the comparative analysis of the normal weight-, and lightweight CSC. They also incorporated the steel fibers (SF) in both sets of mixes in the range of 0 to 2%. It was found that the addition of both CS and SF together doesn't have any significant effect on the slump values of the concrete, because it was found in the range of 5-8 mm. However, the addition of 2% steel fibers showed about 7% higher dried density compared to the mixture without the fibers. Abirami *et al.* (2016) also utilized the coconut shell as coarse aggregate and prepared four mixes, first were control NWC and other mixtures the replacement was 5, 15 and 25%, respectively. All the mixes contain the same *w/b* ratio of 0.45, mix proportioning of 1:2:4 and cement content of 383 kg/m^3.

Magrey *et al.* (2016) prepared sixteen mixes by considering two types of coarse aggregates as NWA and CS, and two types of fine aggregates as sand and glass powder. The w/b ratio of 0.45, mix proportioning ratio of 1:1.5:3 and cement content of 440 kg/m^3 were placed constantly in all the mixes. The slump values for all the mixes were found in the range of 16 to 75 mm. Subramani and Anbuvel (2016) investigated the behaviour of reinforced concrete beams using CS lightweight concrete. They prepared five mixes, first was control NWC, in the remaining mixes the total replacement of NWA was 20% with an interval of 5%. Similarly Sathishkumar and Kumar (2017) prepared five mixes with maximum replacement up to 10% at an interval of 2.5%. They reported the slump values in the range of 63-84 mm. Kamal and Singh (2015) and Jeyapriya and Kamalnataraj (2017) prepared the lightweight concretes using the CS aggregates. The incorporation of CS was up to 30% at an interval of 10%, both studies have used the same w/b ratio of 0.44.

Kumar *et al.* (2017) studied the compressive strength by partially replacing the CS and the fibers in the conventional concrete. They prepared 10 mixes and replaced NWA with CS up to 15% at an interval of 5% and for each set of three mixes, the fibers were also added. Patel and Arora (2015a) also investigated the CSC by using CS as coarse aggregates, first mixture was a control made of conventional materials, however, in the remaining five mixes the CS aggregates were incorporated up to 50% substitution levels at an interval of 10%. Rao *et al.* (2015) studied the compressive strength of the CSC with the maximum replacement up to 20% and the w/b ratio was in the range of 0.43 to 0.51. Similarly, the contribution level up to 20% was also utilized by Mohapatra and Parhi (2017), who considered the w/b ratio of 0.45 and reported the slump values in the range of 27 to 38 mm. Some studies (Harle 2017, Pavani and Ramarao 2016, Reddy *et al.* 2017) utilized the highest substitution level of CS to prepare the structural lightweight aggregate concretes, the substitution levels were up to 45%, and the w/b ratios were placed in the range of 0.5 to 0.55, and the slump values were found in the range of 50 to 100 mm.

Adebakin *et al.* (2018) prepared 5 mixtures from 35 initial trial mixes of self-compacting lightweight-aggregate concrete (SCLWC) using CSA as coarse aggregate and blended with various contents of fly ash (0-25%) as a replacement of cement at the same percentage of superplasticizer (1.75% by weight of binder) and binder ratio of 0.33% to examine/check/perform the experimental works on the mix design. It was concluded that no pre-treatment is required for coconut shell aggregate to produce flowable concrete. Slump flow, viscosity and passing ratio values increased due to the replacement of cement with fly ash. This study infers the use of SCLWC using coconut shell as coarse aggregate blended with fly ash can be used in the construction of walls, beams, columns, and slabs without the issue of honeycomb or segregation and excessive bleeding.

Thilagashanthi *et al.* (2021a) investigated the treatment methods on CS aggregates using ferrous sulphate (FS) and polyvinyl alcohol (PVA). They reported a significant reduction in water absorption in the CS aggregates after being treated. Barveen *et al.* (2018) conducted a study to explore the CSC using rice husk ash (RHA) as cement replacement and CS as coarse and reported that the addition of RHA increases the workability, however, the density of the mixes was reduced as percentage substitution increases. At 28 days of age, the compressive strength increased up to 10% RHA in CC and CSC. The flexure strength and splitting tensile strengths were 14.81% and 11.43% of its compressive strength (26.67 N/mm^2) at 28 days of age.

Recently, Pordesari *et al.* (2021) reported the engineering properties of CSC and reported that the density and slump values were decreased as the CS content increases in the mixture. Splitting tensile and compressive strengths were reduced and water absorption of CSC was increased. Based on various properties, it was found that CSC performed well compared to OPS-LWC.

The comparative behavior of lightweight-, and normal weight concretes using the CS and NW aggregates was studied by Afolayan *et al.* (2017). They preferred the size of CSA as 16 mm and found the compressive strength of 1.15 and 7.8 MPa at 3 and 28-days, respectively. Furthermore, the density of CSC was found between 1542 and 1782 kg/m^3. A similar comparative study of normal-, and LWC using CS aggregates was performed by Shelke *et al.* (2014), who focused on the strength characteristics and the cost analysis of CSC mixes. In conclusion, it was found that as CS replacement increases the compressive strength decreases, whereas, the cost per m^3 of concrete made with CS aggregates was reduced compared to NWC. The 28-day air-dried density of CSC was found lower than 2000 kg/m^3 and it can be considered as structural lightweight aggregate concrete. CS aggregates are helpful in low-rise and low-cost housing and buildings and can be considered as environmentally-friendly construction material (Ghosal and Moulik 2015).

Shinde *et al.* (2016) investigated the normal-, and LWCs, the CS aggregates were partially substituted in the NWC at the percentages of 0%, 10%, 15%, 20% and the 28-day compressive strength for 20% CSC mixture was found about 9.75 MPa, and it was about 69% lower than the control concrete. The compressive strength of CS lightweight concrete containing CS as fine aggregate was investigated by Otunyo *et al.* (2014). They prepared the mixes with a fixed w/b ratio of 0.5 and found the slump values in the range of 0 to 30 mm. It was reported that the compressive strength of the concrete decreased with an increase in the replacement of fine aggregate with CCS. The compressive strengths results obtained at 14, 21 and 28 days are 15.17 MPa, 15.4 MPa and 16.44 MPa, respectively.

7. Hardened density of CS concrete

The fresh density of coconut shell concrete (CSC) using the CS aggregate was observed in the range of around 1975 - 2110 kg/m^3 (Gunasekaran and Kumar 2008). Some of the CSC mixes showed a density ranging from 1542 kg/m^3 to 1782 kg/m^3 which is within the lightweight concrete density (Afolayan *et al.* 2017). The hardened density of CSC was found in the range of 1880 - 1930 kg/m^3 (Gunasekaran and Kumar 2008). The concrete containing 0% CS means the control conventional concrete showed the average hardened density of about 2360 kg/m^3 (Leman *et al.* 2017). Whereas, the CSC mixes showed the density in the range of 1865-1990 kg/m^3 (Gunasekaran *et al.* 2011). The variation in the density of the concrete with crushed CS replacement in the concrete with 1:2:4 mix ratio was found in the range of (1.95-2.66)*103 kg/m^3 (Otunyo *et al.* 2014). Most of the CSC mixes showed the hardened density in the range of 1996-2300 kg/m^3 (Subramani and Anbuvel 2016), however, it decreases as the percentage of coconut shell in the concrete increases. In another study, the density range was found between 2240-2408 kg/m^3 (Dandagala *et al.* 2014, Kamal and Singh 2015). Some studies (Harle 2017, Kumar *et al.* 2016) revealed that the CS aggregates can produce the CSC with the hardened density in the range of 1930 to 1990 kg/m^3.

8. Mechanical properties of CS concrete

In this section, the mechanical properties of CSC including compressive-, flexural- and splitting tensile strengths were thoroughly discussed.

8.1 Compressive strength

The quality of structural concrete in terms of compressive strength is considered as the foremost suitable property for any innovative material fabric utilized in the development industry. It influences all the other mechanical properties of the blend such as modulus of rupture, splitting tensile strength, elastic modulus, and shrinkage. ACI recommended that the 28-day cylindrical compressive strength of the structural LWC should be more than 17 MPa (Neville and Brook 2008). Several researchers have explored the structural CS-LWAC with different mix design proportions, CSA as fine and coarse and different curing conditions.

Yerramala and Ramachandrudu (2015) investigated CSC containing 300 kg/m^3 cement and w/b ratio of 0.6, replacement of NWAs was up to 20%. The 28-day compressive strength was found between 7 and 13.5 MPa with reduction range of 35-69% compared to NWC. Further, Afolayan *et al.* (2017) reported 28-day strength of 19.1 MPa using 16 mm CS aggregate size and this strength is more than 17 MPa, a minimum requirement for the SLWC (Aziz *et al.* 2022, Gunasekaran and Kumar 2008, Gunasekaran *et al.* 2008). In NWC, the CS were replaced up to 50% at an interval of 10% and compressive strength was found between 10 and 21.5 MPa (Anwar *et al.* 2016), Likewise, Shinde *et al.* (2016) achieved a 28-day compressive strength of 9.75 MPa at 20% CS aggregates in NWC. Further, the compressive strength of 30 MPa was achieved at 10% CS replacement in NWC (Chakravarthy *et al.* 2017, Leman *et al.* 2017).

Abirami *et al.* (2016) studied the exploitation of CS as coarse aggregate in concrete with the replacement level at 15, 25 and 30% of the NWAs with w/b ratio of 0.45 and mix proportion of 1:2:4, for CSC mixes, on average, they achieved the 28-day compressive strength values between 21 and 25 MPa. Kamal and Singh (2015) studied the compressive strength of M25 grade CSC by considering the w/b ratio of 0.44 and the replacement of NWA was up to 30%. They reported the 7-day compressive strength in the range of 12 to 20 MPa and the 28-day compressive strength found in the range of 20-29 MPa. Similarly, the 28-day compressive strength of CSC was reported in the range of 22 to 31.3 MPa (Mohapatra and Parhi 2017). Gunasekaran *et al.* (2011) prepared 20 mixes with varying w/b ratios in the ranges of 0.42 to 0.72 and reported 28-day compressive strengths in the range of 4-26 MPa, later they reduced the w/b ratio from 0.38 to 0.48 and reported 28-day compressive strength in the range of 13 to 27 MPa.

A comparative study of CS and glass waste powder has been investigated by Magrey *et al.* (2016). They prepared several mixes by considering a constant w/b ratio of 0.45 and cement content of 440 kg/m^3 and reported the 28-day compressive strength in the range of 24 and 38 MPa. Sathishkumar and Kumar (2017) performed an experimental study on improving the strength properties of CS as coarse aggregate in CSC. The incorporation of CS in NWC was up to 10% at an interval of 2.5% and reported the 28-day compressive strength as 34 to 36 MPa. Similarly, Subramani and Anbuvel (2016) utilized the CS up to 20% and found the 28-day compressive strength value for all mixes of about 19 MPa. In both studies, it was observed that the incorporation of CS aggregates up to 20% in the NWC showed similar strength to the control mixture. Furthermore, Jeyapriya and Kamalnataraj (2017) prepare the modular bricks using the CS aggregate up to 30% substitution level. The 28-day compressive strength value on average was found at about 22.5 MPa.

Kumar *et al.* (2017) investigated the compressive strength of CSC by incorporation of CS and the fibers. The contribution level of CS was up to 15% and they reported the 7-day and 28-day compressive strengths in the ranges of 9-22 MPa and 15-23 MPa, respectively. Some researchers (Mohapatra and Parhi 2017, Rao *et al.* 2015) utilized CS aggregates up to 20% and reported the 28-day compressive strength between 22 and 38 MPa. Several researchers have prepared the SC lightweight concrete containing CS aggregates up to 50%. Patel *et al.* (2015a) utilized 50% CS in the conventional concrete and reported the 28-day compressive strength between 15 and 21 MPa. However, the substitution level of 40% was selected by Harle (2017), and selected the w/b ratio of 0.5 and cement content of 394 kg/m^3 and reported 7-day and 28-day compressive strength between 9-17 MPa and 2-24 MPa, respectively. Furthermore, the incorporation of CS from 5 to 35% at an interval of 5% showed 28-day compressive strength between 20 and 25 MPa (Reddy *et al.* 2017).

Pavani and Ramarao (2016) studied the effect of partial replacement of cement by silica fumes (SF) and NWA by CSA on the properties of the concrete. They prepared three sets, each set containing three mixes, in the first set the CS replacement was 15% for all three mixes, however, in the other two mixes the SF was used at 10 and 15% replacement of cement. Similarly, set 2 contains the CS level of 30% and SF levels were the same as in the first set, vice-versa the third set contains a CS level of 45%. The first set showed 28-day compressive strengths between 26 and 34 MPa, the second set showed these values between 22 and 30 MPa, and the final set showed the same value for all mixes of about 18 MPa. It was found that the substitution of 15% with the SF up to 15% showed better performance compared to control and other CSC mixes.

Otunyo *et al.* (2014) performed the exploratory study on crushed CS as a partial replacement of sand in concrete. They found the slump values and 28-day compressive strength as 0-30 mm and 4 to 13 MPa, respectively. Barveen *et al.* (2018) investigated the mechanical and workability properties of CSC using the replacement of RHA at levels of 0 to 12% with an interval of 2%. They reported that the incorporation of 10% RHA improves the workability and mechanical properties of CSC compared to conventional concrete. Kumar *et al.* (2019) prepared the CSC mixtures using an additional binder as ground granulated blast-furnace Slag (GGBFS) and its optimum was about 10% of OPC replacement and compressive strength was improved by about 15%. GGBS increases the strength of concrete to around 15%. Furthermore, Kumar and Gunasekaran (2019a, b) explored the bond strength of CSC through an inverted metallurgic microscope using alccofine and silica fumes. They reported that the addition of 10% alccofine gave better compressive strength compared to other replacement levels which shows its better bond performance. Similarly, 10% addition of silica fume improves the compressive strength and the bonding layer was found inversely proportional to the age.

8.2 Flexural strength/modulus of rupture

The flexural strength for CS concrete reported by the number of researchers is shown in Table 3. Selwyn and Mahendran (2014) studied the performance of CSC by partial replacement of CS aggregates and reported the 28-day flexural strength in the range of 2.59-3.23 MPa. MOR values decrease with the increase in percentage replacement of CS. The flexural strengths for the specimens with NWA, 10% CS, 20% CS, and 30% CS were found around 8MPa, 6.9MPa, 6MPa, and 6MPa, respectively (Kamal and Singh 2015). Gunasekaran *et al.* (2011) investigated the mechanical properties and bond performance of CSC mixes and reported flexural strength for only a few specimens found in the range of 4.23 to 4.68 MPa, which were about 5-18% of the 28-day compressive strength.

Chakravarthy *et al.* (2017) investigated the CSC up to 2% replacement of CS aggregates and at 1.5% of CS replacement, they achieved the MOR value of 5.87 MPa which was about 20% higher than the MOR value of the conventional NWC. However, this value was about 20% of the 28-day compressive strength. Abirami *et al.* (2016) performed the CSC mixes up to 25% contribution of CS aggregates. They reported the MOR values in the range of 2.36 to 3.36 MPa, however, the control mixture showed the MOR value of 3.17 MPa, it was found that the incorporation of 25% CS aggregate in the NWC showed better flexural strength values compared to conventional concrete.

Magrey *et al.* (2016) investigated the comparative study of CSC and glass powder. Generally, in all CS and glass powder mixes the flexural strength values were found between 7.4 and 8.5 MPa, and the control mixture showed this value of about 8.1 MPa. Furthermore, the mixture C30F10 containing 30% CS and 10% glass powder showed the highest value for MOR of about 8.45 MPa, which was about 4% higher than the NWC. In another study, the flexural strength values for CSC mixes containing CS aggregates up to 10% were found between 3.63 to 4.15 MPa (Satishkumar and Kumar 2017).

Some researchers (Patel *et al.* 2015a, Reddy *et al.* 2017) utilized the CS aggregates as a partial replacement of conventional materials beyond 35% and up to 50%, and the flexural strength values were found in the range of 2.10 to 3.58 MPa. However, Pavani and Ramarao (2016) investigated three substitution levels of CS with the different percentages of silica fumes. It was found that the mix containing 15% of each CS and SF showed the 28-day flexural strength of about 6.21 MPa, which was 13% lower than NWC, and this reduction for mixes C30-SF15 and C45-SF15 were about 22% and 30%, respectively. Jayan and Gunasekaran (2017) also investigated the coefficient of modulus of rupture of CSC and reported that the co-efficient of modulus of rupture for CSC was significantly higher compared to NWC because of fibers in shells.

8.3 Splitting tensile strength

Similar to compressive strength, in specific designs such as airfield highway slabs, shear strength slabs, and cracking resistance, the tensile strength is an important concern (Neville and Brook 2008). Yerramala and Ramachandrudu (2015) reported the splitting tensile strength for CSC mixes between 0.8 to 1.51 MPa at the w/b ratio of 0.6, and these values were about 11% of the 28-day compressive strength. The splitting tensile strength at 7-, 14-, and 28 days were reported between 1.35-2.33 MPa, 1.98-2.68 MPa, and 2.33-3.42 MPa, respectively (Kamal and Singh, 2015). Gunasekaran *et al.* (2011) explored the mechanical properties and bond performance of CSC mixes and reported splitting tensile strength for only a few specimens found in the range of 2.38 to 2.70 MPa, which is on average about 10% of the 28-day compressive strength.

Chakravarthy *et al.* (2017) investigated the CSC up to 2% replacement of CS aggregates and at 1.5% of CS replacement, they achieved the splitting tensile value 3.07 MPa which was about 14% higher than the value of the NWC. However, this value was about 11% of the 28-day compressive strength. Abirami *et al.* (2016) performed the CSC mixes up to 25% contribution of CS aggregates. They reported the splitting tensile values between 2.5 and 2.63 MPa, however, the control mixture showed this value of 2.82 MPa. Subramani and Anbuvel (2016) investigated the CS concrete by incorporating the CS aggregates up to 20% and reported the splitting tensile results between 0.8 and 2.12 MPa, and the control mixture showed this value of about 2.39 MPa. Rao *et al.* (2015) and Mohapatra and Parhi (2017) prepared the CS concrete by considering the replacement of NWAs with CS up to 20%. The splitting tensile strength values were found between 2.19 and 3.70 MPa and it was found that the contribution of 20% CS with a w/b ratio of 0.45 showed similar results to the control conventional concrete.

Some researchers (Patel *et al.* 2015a, Reddy *et al.* 2017) utilized the CS aggregates as a partial replacement of conventional materials beyond 35% and up to 50%, and the splitting tensile strength values were found between 0.66 and 2.71 MPa. However, Pavani and Ramarao (2016) investigated three substitution levels of CS with the different percentages of silica fumes. It was found that the mix containing 15% of each CS and SF showed the 28-day splitting tensile strength of about 2.98 MPa, which was about 5% lower than the NWC, and this reduction for mixes C30-SF15 and C45-SF15 were about 15% and 22%, respectively.

9. Drying shrinkage, elastic modulus, fire and sound resistance and bond behaviour

The pore structure of CSC using scanning electron microscope (SEM) was investigated by Gunasekaran *et al.* (2012), it measures the fissure between the CSA and cement matrix. As the age increases, the fissures being narrowed-down which shows the better bonding ability in CSC. Generally, the theoretical bond strength for plain and deformed bars in NWC were 1.4-1.45 N/mm^2 and 2.24-2.58 N/mm^2, respectively. Thilagashanthi *et al.* (2021b) performed the microstructural pore analysis of treated CS aggregate using SEM. They reported that it is possible to reduce the water absorption of CS aggregates up to 0% by proper treatment.

Prakash Chandar *et al.* (2020) studied the effect of plastic shrinkage properties using river sand and quarry dust in coconut shell concrete. It was found that with the increase in quarry dust percentage area of plastic shrinkage crack decreased. At 100% dosage of quarry dust (QD) concrete the compressive strength was 7.44% higher compared with the 100% dosage of river sand (RS) concrete. At 100% dosage of quarry dust (QD) concrete the total crack area reduced up to 13.2% compared with the 100% dosage of river sand (RS) concrete. This study encourages the use of quarry dust as a replacement for river sand in coconut shell concrete. Prakash Chandar *et al.* (2020) determined the effect of quarry dust (QD) replacement in place of river sand (RS) on the deflection properties of coconut shell concrete (CSC) slabs of five concrete mixes. Total 45 cubes were tested on 3, 7 and 28 days of age to check the compressive strength and density for each mix. Density, slab central deflection and compressive strength were reduced with the increase in QD percentage. The mix slab prepared with 100% river sand was delayed in breaking at the ultimate stage compare to the mixing slab where 100% QD was used.

Ramasubramani and Gunasekaran (2022a) explored the effect of manufactured sand (M-sand) on the deflection abilities of CSC in the slabs. They prepared 5 sets of CSC mixes with replacement levels of sand by M-sand at 0, 25, 50, 75 and 100%. It was observed that both CC and CSC showed enhancement in strength and satisfactory deflection as per IS 456:2000 limitations. Furthermore, the use of M-sand in the CSC mixture also improved the compressive strength and plastic shrinkage cracks were significantly reduced, which enhances the durability of the concretes (Ramasubramani and Gunasekaran 2022b). In addition, the CS with M-sand also performs better and produces eco-friendly geo-polymer concrete (Nithya *et al.* 2021).

Gunasekaran *et al.* (2013a) compared the effect of different coconut shell aggregate percentages on deflection characteristics and plastic shrinkage cracking of coconut shell concrete slabs with conventional concrete. From five concrete mixes containing different dosages of the concrete shell (CS) as coarse aggregates, five slabs, and forty-five cubes were tested. Compressive strength and density of concrete were decreased when the percentage of CS increased. The deflection decreased and plastic shrinkage crack area increased when the percentage of CS decreased. In addition to the above properties, compared to conventional concrete the coconut shell concrete shows ductility property, and CS can be used as a potential building material.

Juluru and Gunasekaran *et al.* (2017) cast the coconut shell concrete (CSC) cylinder specimens to predict the coefficient of modulus of elasticity through stress-strain characteristics. Compressive strength, elastic modulus, density, and ultimate strain of CSC were lower than conventional concrete. The coefficient of modulus of elasticity obtained after regression analysis by strain gauges and compressometer were almost similar i.e., for secant modulus 1702 and 1560. A maximum strain of 0.002 was obtained for the coconut shell.

10. Performance of reinforced and prestressed CSC beams under static and fatigue

Mo *et al.* (2014) reported that for the production of reinforced concrete beams using CS, OPS and OPBC aggregates the ductility performance in all cases significantly increases. Gunasekaran *et al.* (2013b) analyzed the flexural behaviour of six reinforced CSC beams and compared them with the six normal control concrete beams. The flexural behaviour of other lightweight concretes was comparable to that of coconut shell concrete. There were no horizontal cracks on beams which indicate no bond failure. At service loads, the crack widths ranged between 0.20 mm and 0.26 mm in CSC. Under flexural loading full strain capacity was achieved and ductility behaviour was shown by the coconut shell concrete beams. This study concluded that coconut shell will become an alternative construction material for normal coarse aggregate.

Gunasekaran *et al.* (2013c) tested four reinforced beams of conventional concrete (CC) and four reinforced beams using CSA with and without shear reinforcements to check the shear behaviour with reinforcement ratios 0.72 and 0.52%. The diagonal shear failure was prominent in beams with no shear reinforcements while flexure failure mode was seen in beams having shear reinforcement. Superior ductility ratios were obtained by coconut shell aggregate concrete (CSAC) beams than the CC beams. There were no horizontal cracks on beams which indicate no bond failure. In CSAC beams, the flexural and shear cracks were nearly twice than CC beams. In CSAC beams without shear reinforcement, shear strength was closer to corresponding CC beams due to good aggregate interlock which was prominent by the development of shorter rough surface narrow cracks. CSAC and steel indicate good bonding due to higher concrete and steel strains for CSAC beams.

Gunasekaran *et al.* (2014) tested in torsion, four conventional concrete (CC) beams and four beams having CSA to study the torsional behaviour with volumetric torsional reinforcement ratios 0.924%, 1.142%, 1.381% and 1.584%. Under torsion, CC beams behave like CSC beams. In calculating cracking torsional resistance, the Macgregor equation was more conservative compared to ACI prediction. In calculating ultimate torque strength and maximum twist, ACI prediction was more conservative than the Macgregor equation. Due to less coconut shell stiffness, CSC beams crack width was slightly more compared to CC beams for their corresponding reinforcement ratios. For beams subjected to torsion, this research study results were helpful to ensure that CSAs can be used instead of NWAs.

Jayaprithika *et al.* (2016) checked the stress-strain behavior of CSC beams blended with ground granulated blast furnace slag. M20 grade was achieved for CSC using OPC of 401 kg/m^3. For CSC, at full stress capacity, the maximum strain was 0.006 and the static modulus of elasticity ranges from 6.9-7.5 GPa. At the ultimate moment, in flexure, the CSC capacity ratio ranged from 1.00 to 1.06. Ductile failure was prominent rather than compression failure for both under-reinforced and over-reinforced as the ductility ratio of CSC varied between 2.68 and 4.90. Soumya *et al.* (2019) studied the reinforced manhole cover slab made of CSC with 10 mm steel reinforcement. In comparison to NWC cover slabs, the CSC cover slabs showed better performance and hence suggested to be used as a manhole cover.

Recently, Gunasekaran and Choudhury (2021) performed a study on portal frames focusing on single-bay reinforced CSC under lateral and dynamic loading. common structural element and used for resisting lateral loads. It was found that CSC frames showed similar results under cyclic push and pull load compared to conventional concrete frames. However, higher ductility and stiffness were observed in CSC frames. Gunasekaran *et al.* (2019) investigated the confining effect of cold and hot-formed steel using CSC with quarry dust and reported that the confinement with hot-formed steel sustained higher loads without any failure, however, the cold-rolled steel improves the flexural performance by about nine times in comparison to the non-confined members.

Furthermore, Thangasamy and Gunasekaran (2020) explored the behavior of Steel-CSC-Steel-composite (SCSCS) beams without shear studs using three different steel plates of 4, 6 and 8 mm. It was observed that as the thickness of the steel plate increases, the moment carrying capacity was also increased. Further, the steel CSC beams showed higher ductility behavior compared to control members. Similarly, Thangasamy and Gunasekaran (2020) also investigated the flexural performance of SCSCS beams with normal and J-hook studs. The J-hook studs and core strength of concrete significantly improve the moment carrying capacity of the CSC steel beams with good ductility behavior. In another study Ramasubramani and Gunasekaran (2020), they explored the CSC with M-sand on the CSC beam-column junction. Compared to NWC-M, the CSC with M-sand showed higher deflection, however, no cracks were observed in both specimens.

11. Permeability

Palanisamy *et al.* (2020) studied the permeability properties of lightweight self-consolidating concrete (SCC) using CSA a partial replacement of NWAs blended with rice husk ash (RHA) and silica fume (SF). At 28 days age 75% CSA concrete compressive strength was higher than 21.72 MPa which is more than structural lightweight concrete strength requirements.

12. Conclusions

The application of CS as LWA to produce CSC was critically reviewed from the existing literature. The chemical, physical and mechanical properties of CS aggregates were discussed and also compared with the other types of LWAs. In addition, the fresh, hardened, and mechanical properties of the CSC mixes were also discussed and compared with the NWC. Based on thorough review, the following conclusions can be drawn

- CS as half piece size varies in the range of 75 to 100 mm, with the shell thickness range of 2-7 mm, however, as an aggregate its size varies in the range of 4.75 to 20 mm, brownish and found in different shapes i.e., curved, flaky, elongate, roughly parabolic and irregular, and its surface texture is slightly rough on convex and fairly smooth on the concave faces.
- Specific gravity of CSA is found between 1 and 1.6, and it is about 26 to 56% lighter than PKS aggregate, about 28 to 41% lighter than the oil-palm-boiler clinker (OPBC), and about 43 to 62% lighter than the conventional crushed granite aggregates. In addition, the crushed

coconut shell (CCS) as fine aggregate showed about 13 to 60% lower specific gravity results compared to the conventional sand as fine aggregate. Furthermore, the CS aggregate showed the highest water absorption values compared to the other types which were about 94% higher than NWAs, 72% higher than PKS, and about 10% higher the OPBC aggregates.

• Los Angeles abrasion values for CS were found in the range of 1.6 to 2.1%. Impact values for CS were found in the range of 1.22 to 15.7% and the crushing values were found in the range of 1.16 to 21.8%. Therefore, it can be said that the CS displays better resistance in abrasion, impact and crushing compared to NWA.

• Incorporation of CS in the NWC affects the workability of the mixes, in some cases, the slump is increased and vice versa, however, its usage with the glass powder showed better slump values.

• The hardened density of CS concrete was found in the range of 1900 to 2300 kg/m^3.

• CSC containing sand and CSA showed the 28-day compressive strength between 2 and 36 MPa with dried density range of 1865 to 2300 kg/m^3. However, the mixes containing CS as coarse and glass powder and sand as fine aggregates showed a strength range between 24 and 38 MPa.

• The CSC mixes showed the 28-day flexural strength values between 2.59 to 8.45 MPa and these values were about 5 to 20% of the 28-day compressive strength.

• CSC mixes showed the 28-day splitting tensile strength values between 0.8 and 3.70 MPa and these values were around 10 to 20% of the 28-day compressive strength.

• Incorporation of CS aggregate in concrete with quarry dust, the increase in quarry dust percentage area of plastic shrinkage crack decreased. At 100% dosage of quarry dust (QD) concrete the compressive strength was 7.44% higher compared with the 100% dosage of river sand (RS) concrete.

• Incorporating CS aggregate in concrete reduces the mechanical properties. The coefficient of modulus of elasticity obtained after regression analysis by strain gauges and compressometer were almost similar i.e., for secant modulus 1702 and 1560. A maximum strain of 0.002 was obtained for the coconut shell.

• The flexural behaviour of CSC was found similar to other types of lightweight concretes. There were no horizontal cracks on beams which indicate no bond failure. At service loads, the crack widths ranged between 0.20 mm and 0.26 mm in CSC.

• The diagonal shear failure was prominent in beams with no shear reinforcements while flexure failure mode was seen in beams having shear reinforcement. Superior ductility ratios were obtained by coconut shell aggregate concrete (CSAC) beams than the CC beams.

• Under torsion, CSC beams behave similarly to conventional concrete. In calculating ultimate torque strength and maximum twist, ACI prediction was more conservative than the Macgregor equation. Due to less coconut shell stiffness, CSC beams crack width was slightly more compared to CC beams for their corresponding reinforcement ratios.

13. Future recommendations

Although, the incorporation of CS in the conventional concretes is a new era for researchers. However, it needs broad exploration to incorporate the different features of the performance of CSC mixes.

• Recently, several countries are producing millions of tons of solid waste materials from the coconut industry every year, which is significantly damaging the environment. In this study, it was found that CS has good physical, mechanical and chemical properties and is suitable to use as a structural alternative material. However, it needs further exploration in terms of the mechanical and durability properties of the CS concretes.

• Most of the mix proportions for CSC showed lesser workability and higher density then 2000 kg/m^3. Therefore, it needs further exploration specifically mix proportions methods.

• Long-term durability behavior in terms of shrinkage and creep of the CSC was examined by only few researchers, it significantly needs a detailed investigation. In addition, the properties such as drying shrinkage, elastic modulus, fire and sound resistance and bond behavior are not defined and need an extensive exploration.

• Very limited studies available on high-strength CS concretes which can be utilized in prestressed members, needs further exploration. In addition, the structural behavior in terms of flexural and shear (with and without shear reinforcement) of CS reinforced concrete beams needs extensive exploration. Structural performance can also be checked for prestressed CSC beams under monotonic and fatigue loading.

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