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Review

Properties of recycled concrete aggregate and their influence in new concrete production

Kho Pin Verian[a,*], Warda Ashraf[b], Yizheng Cao[c]

[a] Laticrete International, Inc., One Laticrete Park North, CT, 06524-3423, USA
[b] Department of Civil and Environmental Engineering, University of Maine, Orono, ME 04469, USA
[c] SSCI, Albany Molecular Research Inc., West Lafayette, IN 47906, USA

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ABSTRACT

This manuscript presents a review of the potential and challenge of using recycled concrete aggregate (RCA) as the substitute for natural aggregate (NA) in concrete mixtures. Using RCA in concrete preserves the environment by reducing the need for opening new aggregate quarries and decreases the amount of construction waste that goes into landfill. The properties of RCA such as specific gravity, absorption, and the amount of contaminant present in it contribute to the strength and durability of concrete. The quality of RCA depends on the features of the original aggregate and the condition of the demolished concrete. Some researchers have reported that the use of RCA degrades concrete properties while others have successfully produced RCA concrete with a performance that matched normal concrete (NC). In addition to the influence of RCA to concrete properties, this paper also evaluates multiple techniques to improve the performance of RCA concrete, reported cost savings in concrete production and recommendations regarding the application of RCA in concrete.

1. Introduction

Concrete is known as one of the most highly consumed construction materials. The primary ingredients of a concrete mixture are cement, aggregates (coarse and fine), water and admixtures (Mindess et al., 2003; National Ready Mixed Concrete Association (NRMCA), 2012). Among the aforementioned components, aggregate takes up about 70% to 80% of concrete's volume. Types of NAs that are commonly used in concrete application consist of crushed stone, sand, and gravel (USGS, 1997). These NAs are obtained through mining natural resources and opening aggregate quarries. The mining process of NAs generally takes place in vast aggregate quarries that involves heavy equipment and consumes an excessive amount of energy. The resources of NAs are abundant but finite (USGS, 1997). Challenges may develop in construction due to depletion and scarcity of the sources, restrictions on opening new sources and the increased production cost. Using recycled aggregate (RA) may help to address some of these challenges (ACPA, 2009; Verian, 2012). RA can be derived from existing concrete, and thus, termed as recycled concrete aggregate (RCA). According to de Vries (1996), the application of RCA in construction works has become a subject of priority throughout many places around the world. As indicators, 10% of the total aggregates used in the United Kingdom (UK) are RCA (Collins, 1996), 78000 tons of RCA were used in the Netherlands in 1994 (de Vries, 1996) while Germany has been aiming a target of 40% recycling rate of its building and demolition waste since 1991 (van Acker, 1998). According the data in 1997, 0.9 million out of 1.06 million metric ton of the recycled old concrete was used for construction in Denmark (Schimmoller et al., 2000). The annual production of recycled materials derived from old asphalt pavement reached 0.8 million metric ton in Sweden in 1999, in which 95% of it was used in the new asphalt pavement (Schimmoller et al., 2000). Florea and Brouwers (2012) have reported that due to the costly landfilling

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Abbreviations: ACI, American Concrete Institute; ASR, Alkali-Silica Reaction; ASTM, American Society for testing Materials; BCA, Benefit-Cost Analysis; BFB, asalt Fiber; CH, Calcium Hydroxide; C-S-H, Calcium Silicate Hydrate; CTE, Coefficient of Thermal Expansion; DHE, Double Hooked-End; FA, Fly Ash; FT, Freeze-Thaw; FHWA, Federal Highway Administration; HCl, Hydrochloric Acid; IN, Indiana; INDOT, Indiana Department of Transportation; ITM, Indiana Test Method; ITZ, Interfacial Transition Zone; L.A, Los Angeles; MMA, Mortar Mixing Approach; NA, Natural Aggregate; NC, Normal Concrete; NMA, Normal Mixing Approach; JRCP, Jointed Reinforced Concrete Pavements; OPC, Ordinary Portland Cement; PP, Pozzolanic Powder; RA, Recycled Aggregate; RAP, Reclaimed Asphalt Pavement; RCA, Recycled Concrete Aggregate; RCPT, Rapid Chloride Permeability Test; RDME, Relative Dynamic Modulus of Elasticity; RMA, Recycled Masonry Aggregate; RMC, Reclaimed Mortar Content; rpm, rotation per minute; SCM, Supplementary Cementitious Material; SEM, Scanning Electron Microscopy; SEMA, Sand Enveloped Mixing Approach; SF, Silica Fume; SR, State Road; SSD, Saturated Surface Dry; TSMA, Two-Stage Mixing Approach; $TSMA_S$, Two-Stage Mixing Approach with Silica Fume; $TSMA_{SC}$, Two-Stage Mixing Approach with Silica Fume and Cement; UK, United Kingdom; U.S., United States; USGS, United States Geological Survey; w/b, water to binder ratio; w/cm, water to cementitious ratio

[*] Corresponding author.

E-mail addresses: kverian@laticrete.com (K.P. Verian), warda.ashraf@maine.edu (W. Ashraf), yizheng.cao@amriglobal.com (Y. Cao).

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process, which I some cases are more costly than recycling, many European countries have set a high bar for their recycling goals – between 50% to 90% of their construction and demolition (C&D) waste production.

In the United States (U.S.), nearly 100 highway paving projects by the mid-1990s had incorporated RCA in concrete for pavements, some of which are derived from pavements exhibiting D-cracking and alkali-silica reaction (ASR) damage (Burke et al., 1992).

As one of the solutions in preserving the environment and as it is rich in potentials, the use of RCA has been rising and is encouraged. For this reason, understanding the characteristics of RCA is critical to assure the success of its application. This manuscript presents information regarding the state-of-the-art of the characteristics of RCA, its effects on concrete properties, and various methods to optimize its application.

2. Benefits of using RCA

Using RCA instead of NA has positive influences in terms of the environment and economics. It can conserve NA consumption thereby reducing the need to open new mining areas (hence, preserve the environment (Mack et al., 2018)) as well as the energy/fuel consumption associated with hauling (for the same hauling distance, energy required to transport RCA is less than that of NA when the unit weight of RCA is lower than NA. The specific gravity of RCA and NA is discussed in Section 6.2). On the other hand, use of RCA reduces construction waste that usually ends up in landfills (Mack et al., 2018). Using RCA may also reduce construction costs. The price for every ton (1000 kg) of various RCA products ranges from $1 to $18 and vary at different areas (USGS, 2000). According to a study by Environmental Council of Concrete Organizations there is an estimated saving of up to 60% by using RAs as a replacement of NAs (Environmental Council of Concrete Organization, 2018). A study conducted at Purdue University, USA reported that using RCA has the potential of reducing cost as much as $2.26–$2.93 per ton (without considering additional potential saving from landfill) of pavement concrete (Verian et al., 2013). This study also developed a benefit-cost analysis (BCA) model which can provide substantial information for RCA usage (Verian et al., 2013). The overall environmental benefit of using RCA based on the life cycle cost analysis of concrete has also been reported by several studies (Ding et al., 2016; Serres et al., 2016; Knoeri et al., 2013; Marinković et al., 2010). A study by Hossain et al. (2016) revealed that the use of coarse RA obtained from the construction and demolition (C&D) waste in Hong Kong reduces the greenhouse gases footprints up to 65% and saves up to 58% of the energy consumption.

Several other studies have implied that concrete made with RCA can be designed in a way to match the quality of concrete made with NA without the need for additional cement. A study by Beltrán et al. (2014) has indicated that at water to cementitious ratio (w/cm) of 0.5, the use of RCA increased the compressive and flexural strengths of concrete when additional cement (up to 34 kg/m^3) was added into the mixture. According to Etxeberria et al. (2007), replacing natural coarse aggregate with RCA at 25% and 50% weight-base replacement levels improved the compressive and tensile strengths of concrete when adjustments in the mixture proportion were applied, such as increasing the amount of cement, lowering w/cm, adjusting the amount of additive and aggregate proportion. Verian (2012), Verian et al. (2011a) and Jain et al. (2012a) have also indicated that concretes containing 30% coarse RCA (w/cm: 0.43) outperformed the control concrete made with NA only (w/cm: 0.44). By using a modified mixing technique (i.e. two-stage mixing approach (TSMA)), Tam et al. have succeeded in improving the properties of concrete containing up to 30% of RCA to a level comparable or even better than the control concrete (Tam et al., 2005; Tam and Tam, 2007; Tam and Tam, 2008). The benefit of TSMA in improving the performance of RCA concrete is also reported by Brand et al. (2015). In his study, Brand et al. (2015) also found that the greatest strength properties of RCA concrete were achieved when the RCA was at least in the partially-saturated moisture state prior the mixing with TSMA method (Brand et al., 2015).

3. Production of RCA

There are many types of materials that can be recycled and used as a substitute for NA in construction. These materials include, but not limited to, concrete, brick (Kabir et al., 2012; Cachim, 2009; Khalaf and DeVenny, 2005), ceramic (Binici, 2007; Torkittikul and Chaipanich, 2010; Medina et al., 2012; Senthamarai et al., 2011; Pacheco-Torgal and Jalali, 2010; Senthamarai and Devadas Manoharan, 2005), rubber (Atahan and Yücel, 2012; Najim and Hall, 2012; Papakonstantinou and Tobolski, 2006; Richardson et al., 2012; Sukontasukkul and Chaikaew, 2006; Topcu, 1995; Batayneh et al., 2008; Sukontasukkul, 2009), glass (Henry and Morin, 1997; Polley et al., 1998; Nemes and Józsa, 2006; Xie et al., 2003; Shayan, 2002; Du and Tan, 2013; Shao et al., 2000; Federico and Chidiac, 2009; Meyer et al., 2001; Ismail and AL-Hashmi, 2009; Canbaz, 2004), etc. This section emphasizes on the RA derived from concrete. RCA is produced by crushing existing concrete to be used as aggregates in new concrete. The production process of RCA should be designed in a way that optimizes the production of usable RCA in terms of both quality and quantity. The quality of RCA is driven by several different factors, such as the quality of the original concrete, the presence of contaminants (Noguchi et al., 2015) and the processing of the RCA itself (ACI Committee, 2001). Several steps in recycling concrete include evaluation of the source concrete, concrete preparation, concrete breaking and removal, removal of any contaminants (i.e. steel mesh, rebars or dowels), crushing the concrete and sizing the RCA, and beneficiation process (removal of any additional contaminants such as old mortar) (ACI Committee, 2001).

4. Percentage replacement of RCA in concrete mixture

The amounts of RCA used in concrete mixtures varied among different researchers as did the inclusion of fine RCA. A brief survey on the replacement levels of NA with RCA is presented in Table 1. The results of the studies presented in Table 1 have indicated that coarse and fine RCA have the potential to be used as aggregates in concrete application.

5. Consideration for using fine RCA

The concern of using fine RCA in the concrete mixture is mainly associated with the higher mortar and impurity contents of the fine RCA as compared to coarse RCA. The adhered and loose mortars contribute to the angularity, rough surface texture and high absorption of fine RCA particles (Evangelista et al., 2015). These properties of fine RCA, in many cases, were reported to be responsible for the workability problems (Obla et al., 2007), reduction in concrete strength, and significant increases in volumetric instability (i.e., shrinkage, creep and coefficient of thermal expansion (CTE)).

A study by Fan et al. (2015) indicated that mortars containing 25% to 100% of fine RCA experienced higher drying shrinkage than the control specimens at all tested ages (7, 14, 21 and 28 days) due to the higher porosity of this constituent which enables water to evaporate rapidly. Smith (2018) observed that fine RCA contained many impurities which degraded the strength of concrete. Zaharieva et al. (2003) stated that the use of fine RCA is often prevented due to its negative effects on concrete. According to the study results by Evangelista et al. (2015), the smaller size fractions (125–500 μm) of fine RCA possess high mortar content while bigger fractions (1–4 mm) of fine RCA present a considerable amount of cracks at the paste-aggregate ITZ. Obla et al. (2007) made an estimation that additional cost (about $2/ton) is required when aggregate producer separates the RCA into coarse and fine fractions as compared to coarse fraction only. Evangelista and de Brito (2007) used fine RCA which is derived from concretes that are specifically made in laboratorial conditions which

Table 1
Percent replacement of RCA used in various studies by different researchers–a brief survey.

No.	Reference	Percent replacement	
		Coarse RCA	Fine RCA
1	Zaharieva et al. (2003)	0% and 100%	0% and 100%
2	Juanyu and Bing (2009)	0% and 100%	0% and 100%
3	Corinaldesi and Moriconi (2009)	0% and 100%	0% and 100%
4	Sturtevant et al. (2007)	0%, 20%, 50%, 100%	0%, 20%, 22%, 25%
5	Xiao et al. (2005)	0%, 30%, 50%, 70%, 100%	0%
6	Verian (2012), Verian et al. (2013)	0%, 30%, 50% and 100%	0%
7	Tam and Tam (2007)	0%, 20% and 100%	0%
8	Rahal (2007)	0% and 100%	0%
9	Olorunsogo and Padayachee (2002)	0%, 50% and 100%	0%
10	Kou et al. (2007)	0%, 20%, 50% and 100%	0%
11	Poon et al. (2004)	0%, 20%, 50% and 100%	0%
12	Smith (2018)	0%, 15%, 30% and 50%	0%
13	Etxeberria et al. (2007)	0%, 20%, 50% and 100%	0%
14	Gomez Soberon (2002)	0% and 100%	0%
15	Afroughsabet et al. (2017)	0%, 50% and 100%	0%
16	Gao et al. (2017)	0%, 30%, 50% and 100%	0%
17	Katkhuda and Shatarat (2017)	0% and 20%	0%
18	Butler et al. (2013)	0% and 100%	0%
19	Kurda et al. (2017a)	0% and 100%	0%, 50%, 100%
20	Salem et al. (2003)	0% and 100%	0%
21	Ait Mohamed Amer et al. (2016)	0%, 20%, 40%, 60%, 80%, 100%	0%
22	Evangelista and de Brito (2007)	0%	0%, 10%, 20%, 30%, 50%, 100%
23	Khatib (2005)	0%	0%, 25%, 50%, 75%, 100%
24	Fumoto and Yamada (1999)	0%	0%, 25%, 33%, 51%, 67%, 76%, 84%, 92%, 100%
25	Pedro et al. (2017)	0%, 50% and 100%	0%, 50%, 100%

were crushed afterwards. This study indicated that the laboratory-made fine RCA can be used up to 30% replacement ratio without having significant effect to the mechanical properties (compressive strength, split tensile, elastic modulus, and abrasion resistance) of the studied concrete (Evangelista and de Brito, 2007). However, it needs to be noted that the fine RCA used in this study is derived by crushing and sieving concretes specifically produced and cured in the laboratory (Evangelista and de Brito, 2007), which may be totally different from the actual exposure condition experienced by concrete in the field.

In mortar application, several studies reported that using fine RCA yielded similar or even better compressive strength than using natural sand due to the more irregular and porous surface (which leads to a possible higher surface area) of fine RCA that enhances the interlocking bond between the aggregate and paste (Neno et al., 2014; Topçu and Bilir, 2010). The hydration between unhydrated OPC particles existing in the RCA with water can also be a possible reason behind the increased strength over time (Braga et al., 2012). A similar or even better compressive strength was also observed in the mortar made with fine recycled masonry aggregate (RMA) when it is compared to the control mortar containing NA (Silva et al., 2009; Correia et al., 2006; Vieira et al., 2016). Such improvement is due to the reaction between the calcium hydroxide of cement paste and alumina (Al_2O_3)/silica (SiO_2) content of the fine RMA which occurs over time (Silva et al., 2009; Correia et al., 2006; Vieira et al., 2016). Another study by Evangelista and De Brito (2014) presented a comprehensive review regarding the studies of fine RCA and its application around the world.

6. Characteristic of RCA

Many studies have reported the differences between the characteristics of RCA and NA (Verian, 2012; Verian et al., 2013; Beltrán et al., 2014; Verian et al., 2011a; Jain et al., 2012a; Olorunsogo and Padayachee, 2002; Poon et al., 2004; Gomez Soberon, 2002; Khatib, 2005; Medina et al., 2014; Kou and Poon, 2013; Ann et al., 2008; Abbas et al., 2009; Fathifazl et al., 2009; Jain et al., 2012b; Kapoor et al., 2016; Evangelista and De Brito, 2010; Silva et al., 2015; Gesoglu et al., 2015; Gokce et al., 2004; Katz, 2003; Limbachiya et al., 2000; Sagoe-Crentsil et al., 2001; Thomas et al., 2013; Shi et al., 2016; Snyder, 2016). These differences are, but not limited to, mortar content, specific gravity, absorption, Los Angeles (L.A.) abrasion resistance, soundness resistance, and the chemical components.

6.1. Mortar content

It is commonly found that some old mortars inherently cling to the surfaces of the original aggregate and becomes part of the RCA product (Verian, 2012). Due to the nature of mortar which is less dense and more porous than the aggregate matrix, this old mortar creates a lighter system in the RCA. The presence of these old mortars eventually increased the absorption capacity and decreased specific gravity of RCA as compared to most NA (Kisku et al., 2017). In the concrete system, the use of RCA with a surface containing adhered mortar layers creates two types of ITZ (old and new) as described in Fig. 1.The porosity distribution of the new ITZ found to be significantly influenced by the initial moisture condition of the RCA and the strength of RCA source concrete (Leite and Monteiro, 2016; Le et al., 2017).

A previous study by Verian (2012), Verian et al. (2013) examined the cross-section of epoxy-embedded RCA particles to determine the

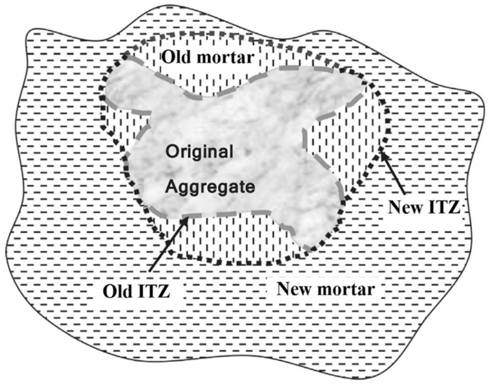

Fig 1. Schematic of old and new ITZ in RCA concrete–adapted from (isku et al. (2017).

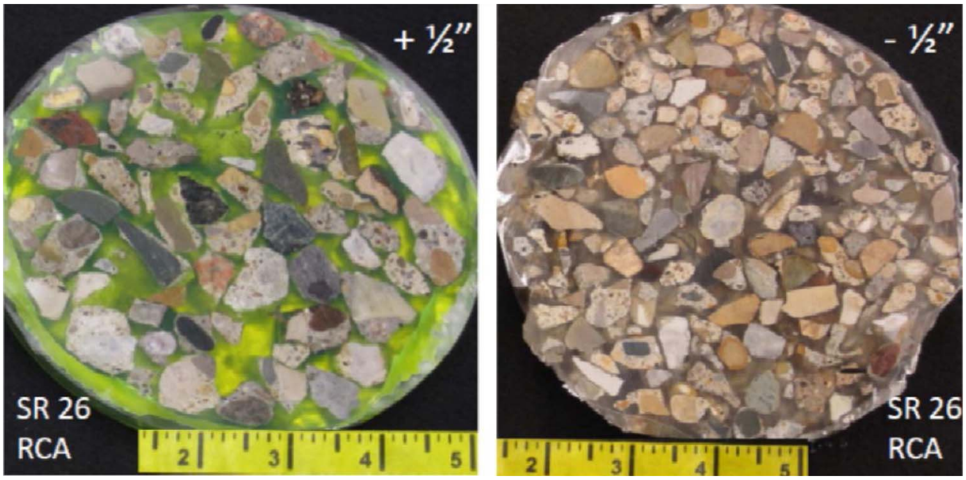

Fig. 2. Cross sections of the sawn surface test specimens made from RCA embedded in epoxy– adapted from Verian (2012), Verian et al. (2013).

percent of mortar adhered to their surfaces by using an optical microscope. The observed specimens are presented in Fig. 2 (Verian, 2012; Verian et al., 2013). The result has indicated that the probability of finding old mortars that were adhered to the surfaces of RCA is up to 28.9% (Verian, 2012; Verian et al., 2013).

Etxeberria et al. (2007) have reported that in the RCA aggregates used in their study, the old mortar contaminants are about 20% and 40% for two different RCA fractions (10/25 and 4/10 mm). Within the range of the findings by Etxeberria et al. (2007), Li (2008) also reported that the adhered mortar can occupy up to 20–30% of the RCA's volume. Afroughsabet et al. (2017) quantified the amount of attached mortar as much as 24% and 38% on two types of RCA used in his study. These RCA traits affect concrete properties and are discussed in more detail in Section 7. Roesler et al. (2013) reported the amount of reclaimed mortar content (RMC) of the coarse RCA at different sizes. As presented in Fig. 3, the RMC of finer fractions of RCA (4.75 and 9.5 mm) is higher than the coarser fractions (> 9.5 mm). In his study, Liu et al. (2011) quantified the amount of old mortar in the RAs reclaimed from concrete with strength grade of 20 MPa and 30 MPa (termed as RA20 and RA30, respectively). The percentages of the old mortar are 42.22% for RA20 and 46.51% for RA30 (Liu et al., 2011).

6.2. Specific gravity

From the collected literature, the specific gravity of RCA is generally lower than that of NA as indicated in Fig. 4(a). The specific gravity of RCA ranges from 1.91 to 2.70 (the only exception is the specific gravity of recycled sanitary ware, which is 2.97 (Vieira et al., 2016))as compared to 2.40–2.89 of NA. As stated previously, the presence of old mortar attached to the RCA is responsible for the lower value of specific gravity of RCA compared to NA (ACPA, 2009). The detail is given in Appendix A, Table A1.

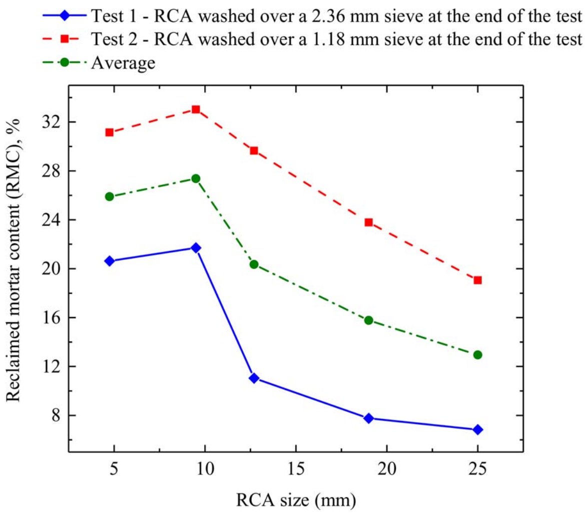

Fig. 3. RMC of different sizes of RCA–adapted from Roesler et al. (2013).

6.3. Absorption

The presence of old mortars on the surfaces of RCA particles leads to higher absorption capacity of RCA as compared to NA due to the somewhat porous nature of the attached mortar (ACPA, 2009; Verian, 2012; Olorunsogo and Padayachee, 2002; Levy and Helene, 2004). Some of these reported values have NA ranging from 0.34% to 3.00% and RCA ranging from 0.50% to 14.75% (as shown in Fig. 4(b), the detail is given in Appendix A, Table A2).

The correlations between the literature collected specific gravity and their respective absorption of the coarse and fine RA are visualized in Fig. 5. It is shown in Fig. 5 that higher absorption correlates to the lower value of specific gravity (except for fine NA which average absorption values relatively constant across the observed range of specific gravity).

6.4. L.A. abrasion test mass loss

In practice, the L.A. abrasion test resulted in% mass loss experienced by the aggregates that take place during the impact of the steel balls and the aggregates. L.A. abrasion mass loss values typically are higher for RCA than for NA. This higher mass loss was caused by the presence of the softer old mortar and the presence of particles that were cracked during the crushing process (Snyder et al., 1994). The L.A. abrasion test results of RCA as compared to NA reported by different researchers are presented in Table 2.

6.5. Soundness durability

Verian (2012), Verian et al. (2013) conducted soundness test on RCA and NA used in his study regarding the application of RCA as coarse aggregate in pavement concrete. The soundness test involves freezing and thawing of aggregates in a brine solution and is used to determine the resistance of aggregate to disintegration by repeated-rapid cycles of freezing and thawing in the presence of sodium chloride solution (Verian, 2012). The soundness test results, in terms of mass loss of RCA and NA, are presented in Table 3.

The soundness test results have indicated that RCA experienced

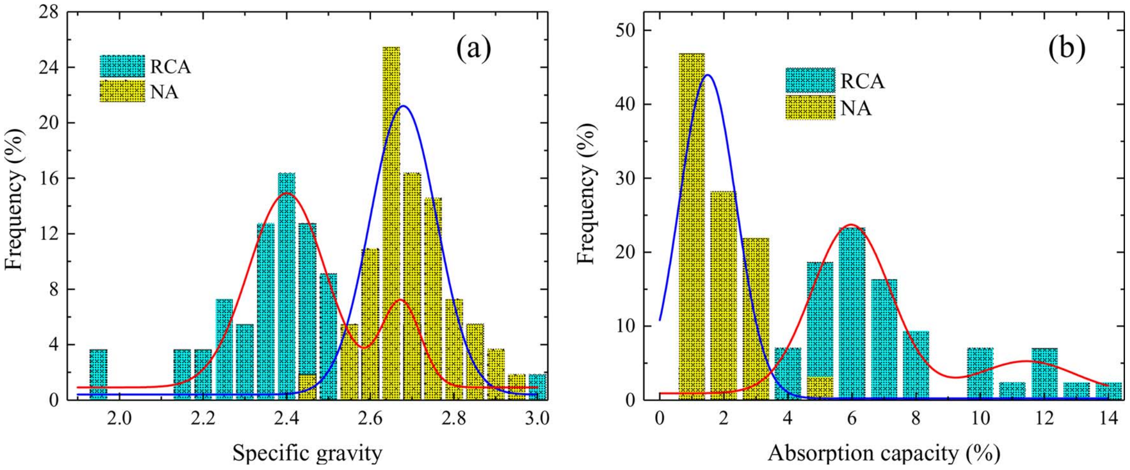

Fig. 4. Frequency distributions of specific gravity (a) and absorption capacity (b) of the RCA.

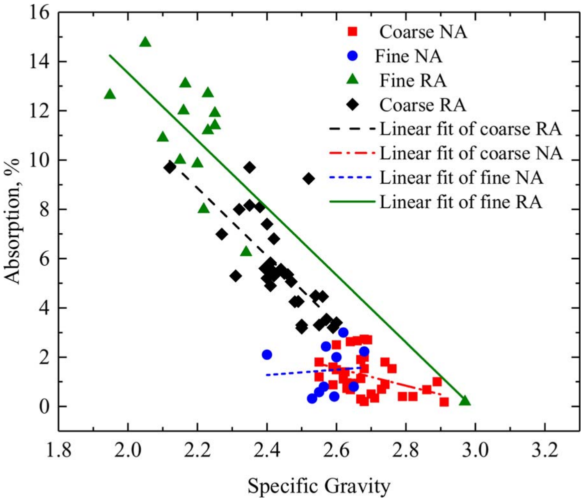

Fig. 5. Specific gravity and absorption of RA and NA used in various studies.

Table 2
L.A abrasion results (% mass loss) of RCA and NA obtained by different researchers–a brief survey.

References	L.A. abrasion mass loss (%)	
	RCA	NA
Snyder et al. (1994)	20–45	15–30
Verian (2012), Verian et al. (2013)	34–36	29–31
Li (2009)	27.3	11.5
Wen et al. (2014)	20–29	15
Yehia and Abdelfatah (2016)	21–35	19–25
Hansen and Narud (1983)	22–41	20–30
Ravindrarajah and Tam (1985)	37–41	18
Ait Mohamed Amer et al. (2016)	51.5	38.9
Kurda et al. (2017a)	43	28
Liu et al. (2011)	42	31

more severe deterioration as indicated by the higher mass loss due to the exposure to FT cycles in the brine solution compared to NA. Another study by Zaharieva et al. (Zaharieva et al., 2003) reported the mass loss of fine and coarse RCA are 25.7 ± 1% and 26.4 ± 0.5%, respectively, as the results of a sulfate soundness test. In their study, Zaharieva et al. (Zaharieva et al., 2003) did not report the value of the sulfate soundness test result for natural sand, but the mass loss value for coarse NA was 3.8 ± 0.5%.

Table 3
Soundness test results of RCA and NA and the maximum limits set by INDOT–adapted from Verian (2012), Verian et al. (2013).

Aggregate	Mass loss after soundness test	INDOT max. limit
#8N1	0.1%[a]–0.5%[a]	30%
#8N2	0.90%	30%
#8R	16.40%	30%
#23 sand	0.9%[a]–9.5%[a]	12%

#8N1: natural dolomitic limestone with max. size of 25 mm.
#8N2: natural dolomitic limestone with max. size of 25 mm.
#8R: RCA with max. size of 25 mm.
#23 sand: natural sand with max. size 4.75 mm.
[a] from INDOT historical data.

6.6. Potassium, chloride and sulfate leachate concentration

The amount of ionic species in the RA is influenced by the exposure condition of the structure (that was crushed and used as the RA source) during its service life. Verian (2012) has reported in his study that the average potassium ion concentration obtained from the leachate solution of RCA derived from SR-26, IN, USA, is approximately 8 times higher than that of NA (see Table 4). This may increase the risk alkali-silica reaction (ASR) on concrete containing RCA. The amount of chloride ion from the leachate solution of RCA is found to be more than double that of NA (Verian, 2012). This finding is not surprising, considering that chloride-based deicers were commonly applied on this pavement throughout its service life, especially during the winter. A study by Rahal (2007) also showed higher chloride content of RCA compared to NA (0.3% vs. 0.14% of cement mass). This RCA is obtained from the demolished old structure in Hawally area, Kuwait (Rahal, 2007), which is located in the sub-tropic climate zone. Higher chloride content makes RCA concrete more prone to corrosion and other chloride-related deterioration when rebars are used in the concrete. Sulfate ion of RCA is found to be less than half of NA which indicates

Table 4
Ion content of aggregate leachates–adapted from Verian (2012).

Type of aggregate	Potassium ion (ppm)	Chloride ion (ppm)	Sulfate ion (ppm)
#8N1	30	377	120
#8N2	32	395	106
#8R	239	851	39

#8N1: natural dolomitic limestone from source 1 (max. size of 25 mm).
#8N2: natural dolomitic limestone from source 2 (max. size of 25 mm).
#8R: RCA (max. size of 25 mm).

the potential of RCA in reducing the risk of internal sulfate attack in concrete as compared to NA (Verian, 2012). The results of the ion chromatography test are presented in Table 4 and the detail of the corresponding test method can be found in the Ref. (Verian, 2012).

7. Characteristic of concrete containing RCA

Aggregate characteristics influence the properties of concrete at plastic and hardened phases (Verian, 2012; Verian, 2015). Therefore, the different quality of RCA compared to NA could differ the performance of RCA concrete and NC (Verian et al., 2013; Etxeberria et al., 2007; Rahal, 2007; Ann et al., 2008; Limbachiya et al., 2000; Levy and Helene, 2004; Kou et al., 2011; Saravanakumar et al., 2016; Federal Highway Administration, 2018).

7.1. Workability

Concrete made with RCA have lower slump than NC at the same w/cm (Smith, 2018; Liu and Chen, 2008; Sturtevant, 2007; Lotfi et al., 2014). The decrease workability of concrete containing RCA is attributed to the higher absorption capacity of RCA, the rougher surfaces and more irregular shapes (Kurda et al., 2017a). In order to achieve similar workability of NC, concrete made with RCA requires approximately 5% to 15% of additional mixing water in the mixture when the RCA used in the dry state (Verian, 2012). Thus, increasing the apparent water to binder ratio (w/b) of concrete when RCA is incorporated in the mixture is commonly practiced (Kurda et al., 2017a). In some cases, this practice can be avoided if the RCA is properly handled and the concrete formulation is designed properly. For example, when the RCA is at or slightly below SSD condition prior to the mixing, similar workability to NC can be achieved (Brand et al., 2015). The use of admixtures (water reducers/plasticizer), fly ash (FA), and the combination of both improves the workability of concrete containing RCA and is commonly used to limit the amount of water (Kurda et al., 2017a; Kou et al., 2011).

7.2. Density

The increased amount of RCA in concrete contributes to the decreased density of RCA concrete (Verian, 2012; Etxeberria et al., 2007; Xiao et al., 2005; Gomez Soberon, 2002). Lower specific gravity and the adhered old mortar on RCA contribute to the lower density of concrete containing RCA. The density of concretes containing various amount of coarse RCA is presented in Fig. 6.

The variation in density of concrete containing RCA is driven by the amount of RCA used in the concrete mixtures and by the variation in the specific gravity of the RCA with respect to that of NA. The density of concrete containing 100% coarse RCA according to Xiao et al. (2005) and Verian (2012) is about 5% less than those made with 100% NAs. In the study by Etxeberria et al. (2007) the density of concrete decreases ~3.3% when all the coarse NA is replaced with coarse RCA. In a study by Dong et al. (2013), 50% of coarse RCA replacement does not significantly affect the concrete density (~0.8% reduction). Marinković et al. (2010) used three different fractions of RCA to replace 65% of NA at different w/cm and has resulted in 4.7%–4.9% lower density as compared to the control concrete.

7.3. Compressive strength

The compressive strength results of various concrete made with different amounts of RCA are presented in Fig. 7. Several studies have reported that the strength development rate of RCA concrete is higher than that of NC, especially at the later age (e.g. 28 days) (Poon et al., 2004; Evangelista and de Brito, 2007; Gesoglu et al., 2015; Kurad et al., 2017). This is due to the remnant of non-hydrated old cement adhered on the surfaces of RCA particles which react with water and thus, increases the rate of strength development (Kurad et al., 2017).

Silva et al. (Silva et al., 2014) performed statistical analysis on the collected data from literature and reported that it is possible to develop a model to predict the strength decrease in concrete containing RCA for different replacement level. This is in agreement with the data presented in Fig. 7(A) and (B) which indicate that compressive strength tends to decrease as the amount of RCA increases. However, Poon et al. (Poon et al., 2004) reported that the influence of RCA replacement level on concrete compressive strength is significantly influenced by the initial moisture condition of RCA. Depending on the moisture level the compressive strength can be reduced by up to 30% or increase up to 20% for 100% aggregate replaced by RCA (see Fig. 8). The phenomena of a lower compressive strength of concrete made with RCA (Tam et al., 2005; Tam and Tam, 2008; Kou et al., 2011; Lotfi et al., 2014; Kong et al., 2010) is attributed to the presence of two types of interfacial transition zones (ITZ) in the matrix. The ITZ represents the bond between aggregate and paste and is normally weaker than either the aggregate or hydrated cement paste. In concrete made with NA, the ITZ occurs between the aggregate and mortar while in concrete containing RCA, the ITZ take place between the original aggregate and old mortar and new mortar (Etxeberria et al., 2007; Tam et al., 2005; Kou et al., 2011; Kong et al., 2010; Lihua et al., 2017) (Fig. 1). Moreover, the lower compressive strength is also driven by the fact that higher amount of water is, in many cases, used in the RCA concrete mixture in order to achieve desirable workability (Kurda et al., 2017a; Kurda et al., 2017c). The presence of old mortar on the surfaces of RCA also

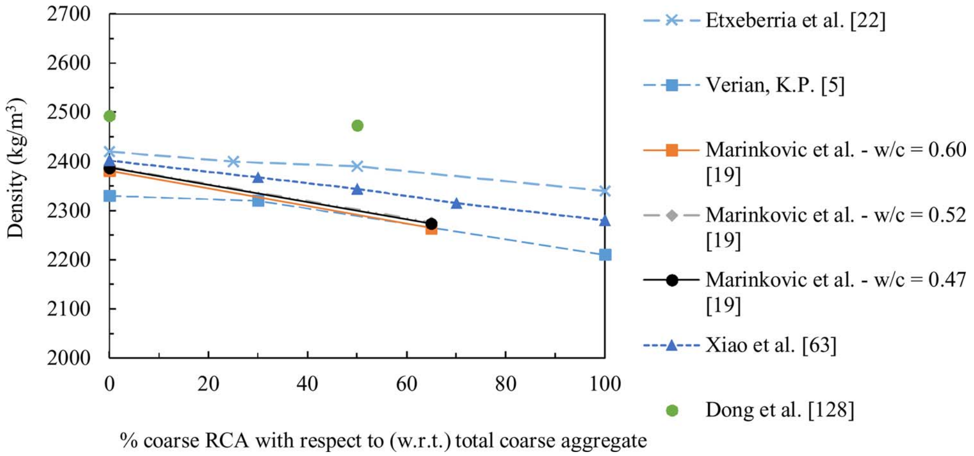

Fig. 6. Density of concrete containing different amount of coarse RCA–adapted from Verian (2012), Marinković et al. (2010), Etxeberria et al. (2007), Xiao et al. (2005), Dong et al. (2013).

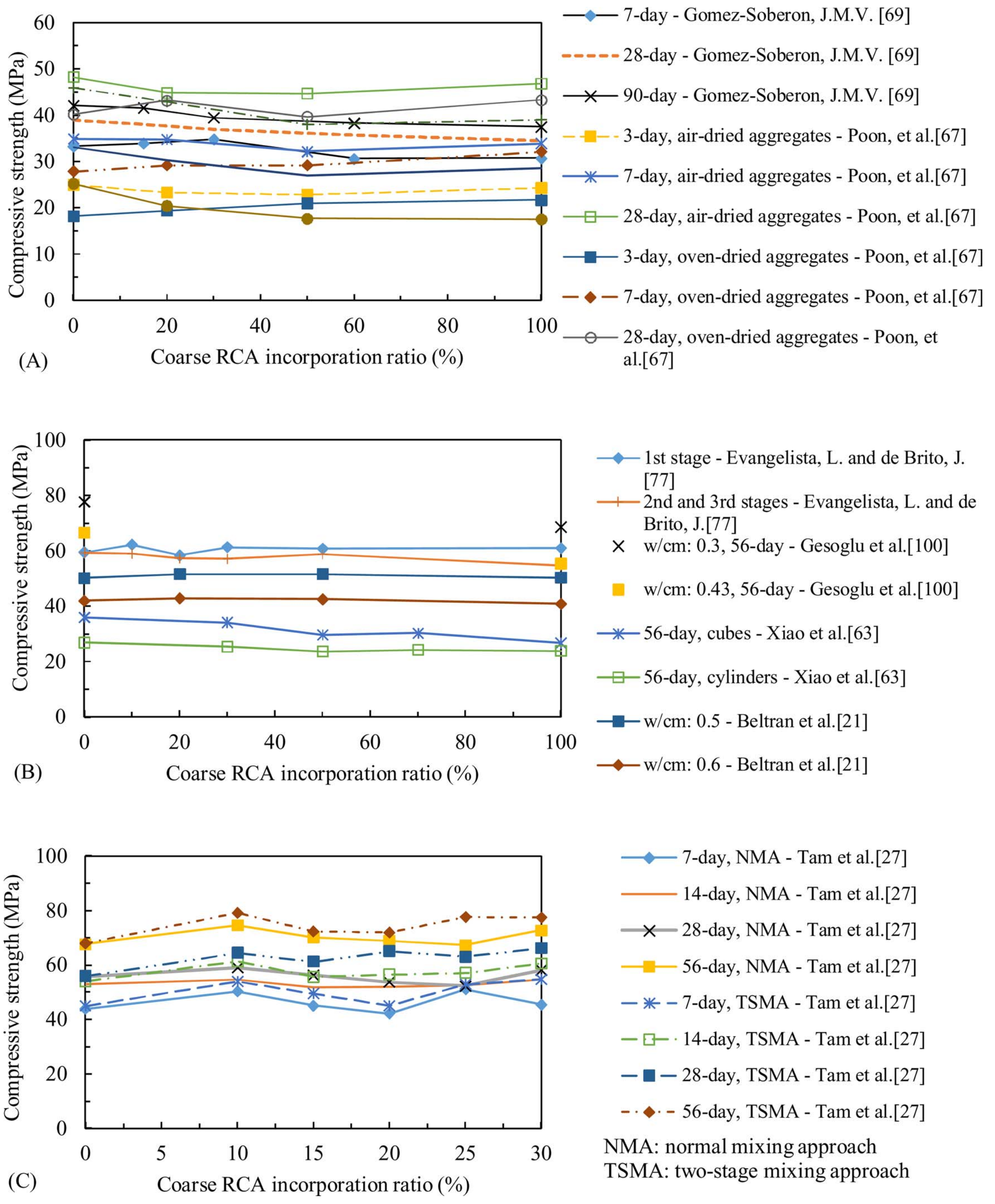

Fig. 7. Compressive strength values of various concretes made with different levels of RCA; (A) adapted from Poon et al. (2004), Gomez Soberon (2002); (B) adapted from Beltrán et al. (2014), Xiao et al. (2005) Evangelista and de Brito (2007), Gesoglu et al. (2015): (C) adapted from Tam and Tam (2008).

contributes to the lower compressive strength of RCA concrete as it possesses lower density (w.r.t. aggregate's density) (Kurda et al., 2017c).

Fig. 7(A) shows that air-dry aggregates produced concrete with higher compressive strength (for normal and RCA concrete) compared to the compressive strength of concretes made with oven-dried and SSD aggregates (Poon et al., 2004). Lowering w/cm improves the compressive strength of both concrete containing RCA and NC (Fig. 7(B)) (Gesoglu et al., 2015). By comparing study by Gesoglu et al. (2015) (w/cm 0.3 and 0.43) and Beltrán et al. (2014) (w/cm 0.5 and 0.6) in Fig. 7(B), the incorporation of RCA in concrete mixture has more significant influence in lowering the compressive strength of concrete made with low w/cm as compared to concrete with high w/cm. This is because, at a high level of w/cm the quality of the new cement paste is closer to that of old mortar than the paste made with low w/cm. These results are aligned with the finding by Kurad et al. (2017) that used fine RCA in their study.

Fig. 7(C) indicates the benefit of the TSMA, developed by Tam and Tam (2008), in producing concrete with higher compressive strength than the concrete produced with the normal mixing approach (NMA). Brand et al. (2015) combined TSMA and the use of saturated RCA to improve the compressive strength of RCA concrete. The detail regarding TSMA is discussed further in Section 8.2.

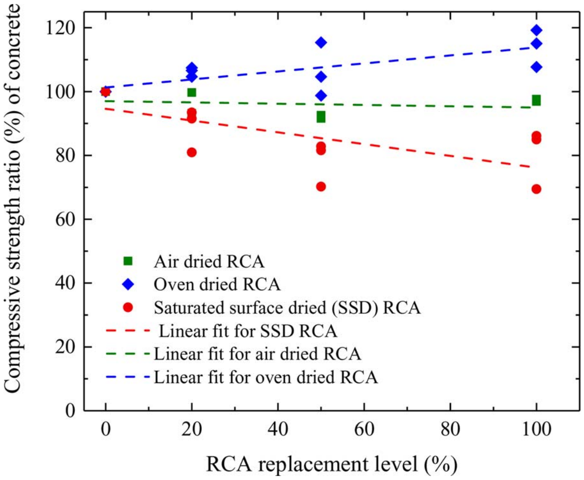

Fig. 8. Compressive strength variation of concrete with RCA replacement levels for different initial moisture conditions. Data from Poon et al. (2004).

7.4. Flexural strength

A study by Katz (2003) has indicated that the flexural strength of concrete made with RCA is ~10% lower than that of NC. The decrease of flexural strength of concrete containing RCA was noticeable especially when saturated recycled aggregate was used in the concrete mixture (Poon et al., 2004; Kou et al., 2011). However, studies by Limbachiya et al. (2000) and Beltrán et al. (2014) have indicated that RCA does not have a significant effect on the flexural strength of concrete. Limbachiya et al. (2000) used three levels of w/cm (0.29, 0.36 and 0.45) for both NA and RCA concrete in their study. Meanwhile, Beltrán et al. (2014) increased the amount of cement (up to 45 kg/100% of RCA replacement level) as the amount of RCA increased. At the same time, Beltrán et al. (2014) also increased the amount of water along with the cement in order to keep the w/cm at 0.5 and 0.6. The flexural strength results obtained by different researchers at various level of RCA in concrete are presented in Fig. 9.

7.5. Tensile strength

A study by Katz (2003) has indicated that the tensile strength of concrete made with RCA is ~6% lower than that of NC. Other studies showed that reduction of tensile strength on concrete containing RCA is up to 10% when only coarse NAs were replaced by coarse recycled aggregates. In case of both coarse and fine NAs replacement by RCA, the tensile strength was further reduced by 10%–20% (ACI Committee, 2001; Federal Highway Administration, 2018; Hansen, 1986). Etxeberria et al. (2007) compensated the potential reduction of tensile strength due to the incorporation of RCA by adding more cement (up to 25 kg/m^3) while keeping the same amount of water. Brand et al. (2015) improved the tensile strength of RCA concrete through TSMA and using saturated (~80% and 100% SSD) aggregate. The tensile strength of various concretes containing different amounts of RCA is presented in Fig. 10.

7.6. Modulus of elasticity (E)

Several studies have indicated that concrete containing RCA has a lower modulus of elasticity (E) than NC, and the reduction is proportional to the increased of RCA used in the concrete mixture (Verian, 2012; Etxeberria et al., 2007; Xiao et al., 2005; Kou et al., 2007; Gomez Soberon, 2002). This loss is associated with the lower E of RA as compared to NA specifically when the other mixture components are kept constant (Silva et al., 2016a). The E value for concrete made with coarse RCA was 10%-33% less than the E of NC (ACI Committee, 2001; Federal Highway Administration, 2018; Hansen, 1986). A study by Xiao et al. (Xiao et al., 2005) indicates that when all the coarse NA is replaced by RCA, the E of concrete reduces by around 45%.The variation of E with respect to the percent coarse RCA replacement in concrete as reported by several researchers is presented in Fig. 11.

As it can be observed from Fig. 11, the elastic modulus can be reduced by up to 20% if 100% coarse NA of the concrete mixture is replaced by coarse RCA. However, based on the literature data, the variation in elastic modulus appeared to be lower (see 95% prediction band in Fig. 11) compared to the compressive strength. From Fig. 11, the linear correlation between E and the amount of RCA is presented in Fig. 12.

7.7. Coefficient of thermal expansion (CTE)

Pavement concrete containing RCA was reported to possess a higher coefficient of thermal expansion (CTE) than the control pavement concrete made with NA only (Sturtevant, 2007). High values of CTE increases the potential for cracking due to higher stress generated due to changes in temperature. The CTE of concrete made with RCA is reported to be up to ~30% higher than the CTE of normal pavement concrete (Hansen, 1986).

7.8. Freezing-thawing resistance

Salem et al. (2003) and Verian (2012) indicated that concrete containing RCA had lower resistance to FT exposure than conventional concrete made with NA due to the higher porosity, which subsequently leads to higher absorption and poorer mechanical performance of concrete made with RCA. Another study Gokce et al. (2004) showed that concrete containing RCA made with recycled coarse aggregates derived from air-entrained concretes has better FT resistance than concrete made with RCA made with recycled coarse aggregate from non-air-entrained concrete after subjected to 500 FT cycles. On the other hand, Bogas et al., (2016) reported that the use of fine RCA as the

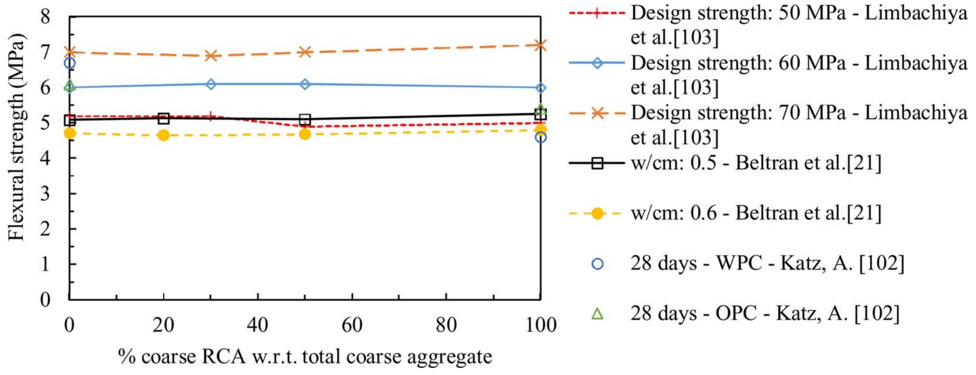

Fig. 9. Flexural strength values of various concretes made with different amounts of RCA–adapted from Beltrán et al. (2014), Katz (2003), Limbachiya et al. (2000).

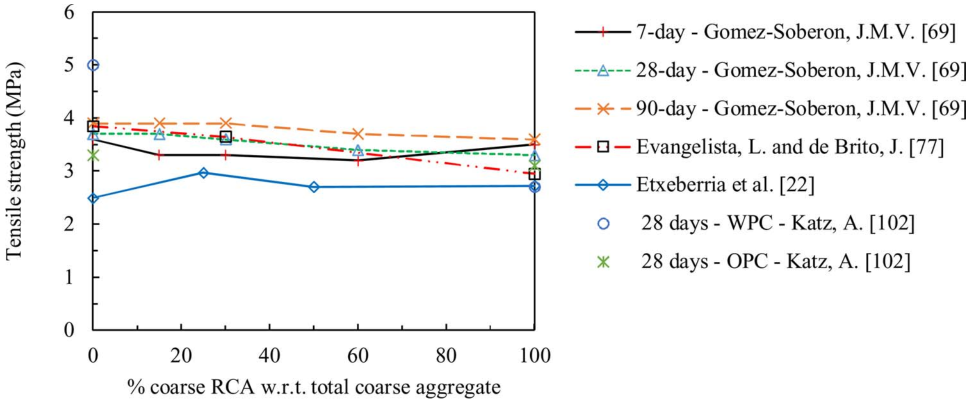

Fig. 10. Tensile strength values of various concretes made with different amounts of RCA–adapted from Etxeberria et al. (2007), Gomez Soberon (2002), Evangelista and de Brito (2007), Katz (2003).

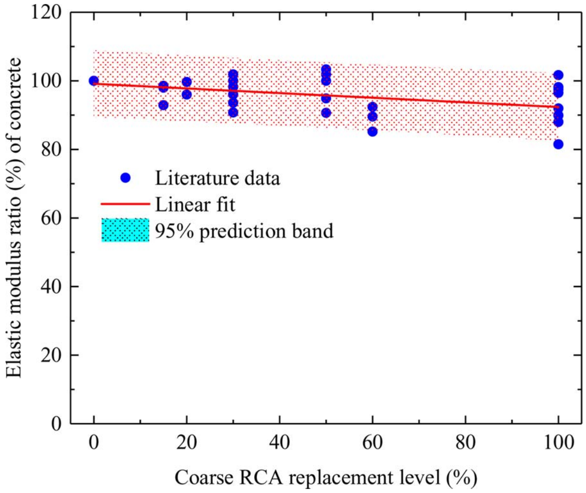

Fig. 11. Modulus elasticity values of different concrete made with different level of coarse RCA as replacement for coarse NA–adapted from Beltrán et al. (2014), Gomez Soberon (2002), Evangelista and de Brito (2007), Gesoglu et al. (2015), Limbachiya et al. (2000).

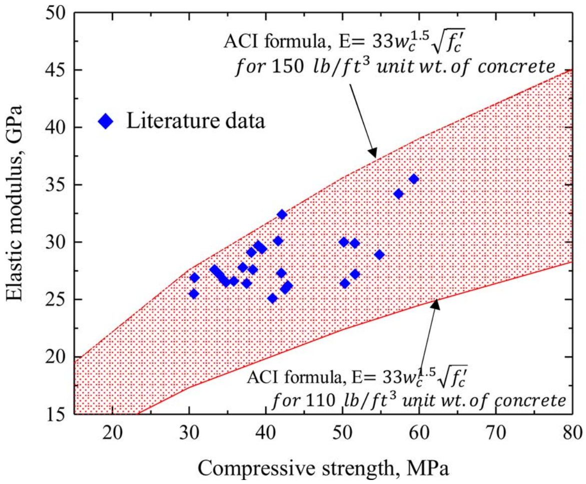

Fig. 12. Relation between E and compressive strength of concrete containing RCA.

replacement of fine NA did not impair the FT resistance of concrete but the scaling resistance. Another study by Lotfi et al. (2014) had resulted in 5.8 MPa reduction in the compressive strength of RCA concrete exposed to FT cycles as compared to 0.4 MPa reduction of its control specimens.

7.9. Drying shrinkage

The extent of the occurrence of drying shrinkage is affected by paste content and w/cm of the concrete (Mindess et al., 2003). Concrete made with RCA generally contains higher paste content due to its reclaimed and new mortar, and thus, concrete containing RCA has higher magnitude of drying shrinkage compare to NC (Verian, 2012; Verian et al., 2013; Beltrán et al., 2014; Khatib, 2005; Evangelista and De Brito, 2010; Sagoe-Crentsil et al., 2001; Snyder, 2016; Sturtevant, 2007). According to the study by Building Contractors Society of Japan (Building Contractors Society of Japan, 1978), as reported by the ACI committee 555, concrete made with coarse RCA and natural sand has 20% to 50% higher shrinkage while concrete made with both coarse and fine RCA has 70% to 100% higher shrinkage compared to NC (ACI Committee, 2001). The incorporation fine RCA induces higher drying shrinkage due to the relatively higher old paste content as compared to coarse RCA which leads to high absorption (Fan et al., 2015). The previous study by the author resulted in more than 0.055% shrinkage for concrete made with 100% coarse RCA after 150 days while the control concrete experienced less than 0.03% shrinkage (Verian, 2012).

7.10. Creep

The creep of concrete containing RCA is found to be proportional to the amount of RCA as the higher amount of RCA in concrete mixture increased the degree of potential creep (Tam and Tam, 2007; Hansen, 1986). Ravindrarajah and Tam (1985) has reported that creep for concrete manufactured from RCA to be 30% to 60% greater than NC. This phenomenon is due to the higher paste volume of RCA concrete compared to NC as creep of concrete is proportional to the amount of paste or mortar in concrete (ACI Committee, 2001). Kou and Poon (2012) reported that the creep strain of concrete made with RCA reached more than 600 μm as compared to less than 500 μm of NC.

7.11. Permeability

The coefficient of permeability of concrete is dictated by the size and continuity of the pores in hydrated cement paste (Mindess et al., 2003). Concrete made with RCA has permeability two to five times higher than that of NC for mixtures with w/cm of 0.5–0.7 (Hansen, 1986). Based on experiments conducted by Zaharieva et al. (Zaharieva et al., 2003), the water permeability of RCA concrete ($k = 1.4 \pm 0.3 \times 10^{-20}\,\mathrm{m}^2$ and $k = 2.4 \pm 0.5 \times 10^{-20}\,\mathrm{m}^2$) is found to be twice than that of NC ($k = 0.8 \pm 0.1 \times 10^{-20}\,\mathrm{m}^2$). A similar result is obtained by Ujike (2000). A study by Bhikshma and Divya (2012) also indicated higher permeability of RCA concrete as compared to NC. Bhikshma and Divya (2012) also found that incorporating up to 30% of FA as OPC replacement in RCA concrete reduced the permeability.

7.12. *Chloride ion penetrability resistance*

As the permeability increases, the chloride ion penetration resistance of concrete made with RCA decreases (Verian, 2012; Jain et al., 2012a; Kou et al., 2011; Verian et al., 2011b). Kou et al. reported that concrete containing RCA made with 100% coarse RCA had more than 40% lower chloride penetration resistance compared to NC (Kou et al., 2011; Kou and Poon, 2012). Rapid chloride permeability test (RCPT, as per ASTM C 1202 (American Society for Testing Materials, 2016)) on concrete made with coarse RCA has a total charge passed off more than 4000C as compared to ~3200C of NC (Verian, 2012; Verian et al., 2013; Jain et al., 2012a; Verian et al., 2011b). The higher passing charge also implies that incorporating RCA in concrete reduces its resistivity (Verian, 2012; Verian et al., 2013; Verian et al., 2011b).

7.13. *Fracture properties*

The quality of the RA and the bond between the aggregate and paste play important role in determining the fracture behavior of concrete. A number of studies have investigated the fracture properties of concrete made with RA. Brand et al. (2014) used reclaimed asphalt pavement (RAP), fractionated RAP, and RCA is his study which indicates despite having lower strengths (compressive, flexural and tensile) and E, concretes containing the aforementioned materials have yielded comparable or in some cases, higher total fracture energy compared to the control. This is in agreement with some other studies that have shown the similar to or even higher fracture capacity of concrete containing RA than NC (Kou, 2006; Amirkhanian, 2012). Other studies found that incorporating RCA in concrete reduces the fracture properties (Roesler et al., 2013; Liu et al., 2011; Amirkhanian et al., 2011). As an example, a study by Ishiguro (1995) indicated that the fracture energy of RCA concrete is 60% of that of NC.

As it can be observed from above discussion, the influence of RCA on concrete properties can vary. Accordingly, to compare the findings, the summarized information is presented in Fig. 13. Apparently, from this figure multiple studies have confirmed same influence of RCA on concrete compressive strength, flexural strength, density, workability, permeability, creep and shrinkage. However, the influence of RCA on fracture properties, FT resistance and tensile strength appeared to be indecisive. Another interesting thing to notice is that most of the studies focused on the mechanical properties of concrete containing RCA. Whereas, only a few studies focused on parameters which are known to influence the long-term performance of concrete, such as FT resistance, permeability, and creep. As such, it is clear that additional studies should be undertaken to investigate the durability and long-term performance of concrete containing RCA.

8. Potential ways to improve the performance of RCA concrete

To compensate the negative influence of the use of RCA in concrete, several efforts to improve the performance of concrete made with RCA are discussed in the following subsections.

8.1. *Using supplementary cementitious materials (SCMs) as partial OPC replacement*

The SCMs that are covered in this manuscript are limited to FA, ground granulated blast furnace slag (GGBFS), silica fume (SF) and metakaolin.

8.1.1. *Fly ash (FA)*

The additional calcium silicate hydrate (C-S-H) which is produced through the pozzolanic reaction of FA that densifies paste matrix of concrete and compensates for the more porous nature of concrete made with RCA (Lothenbach et al., 2011). The source of CH which is required for pozzolanic reaction in RCA concrete is not only from the hydration between new cement and water but also from the old mortar attached on the surface of RCA particles (Kou and Poon, 2013). The benefits of using FA are as follows:

- FA improves the workability of concrete (Paleti, 2011; Jalal et al., 2015; Hale et al., 2008)
- FA reduces the permeability of concrete, limiting the penetration of water and/or other liquids that may damage the concrete (Verian, 2012; Verian, 2015; Kou and Poon, 2012; Verian et al., 2011b; Verian et al., 2015; Kurda et al., 2017b)
- FA improves the compressive strength of concrete at later age (Verian, 2012; Verian, 2015; Hale et al., 2008; Kurda et al., 2017b; Weng et al., 1997; Liu et al., 2000)
- FA improves the performance of concrete exposed to FT cycles (Verian, 2012; Verian, 2015) and chloride-based deicers (Verian, 2015; Verian et al., 2015; Kurda et al., 2017b)
- FA reduces the shrinkage of concrete containing RCA (Verian, 2012; Verian et al., 2013; Kou and Poon, 2012; Kurda et al., 2017b)
- In a condition which favorable for carbonation (RH 40%–70%), FA has the potential in increasing CO_2 sequestration in concrete

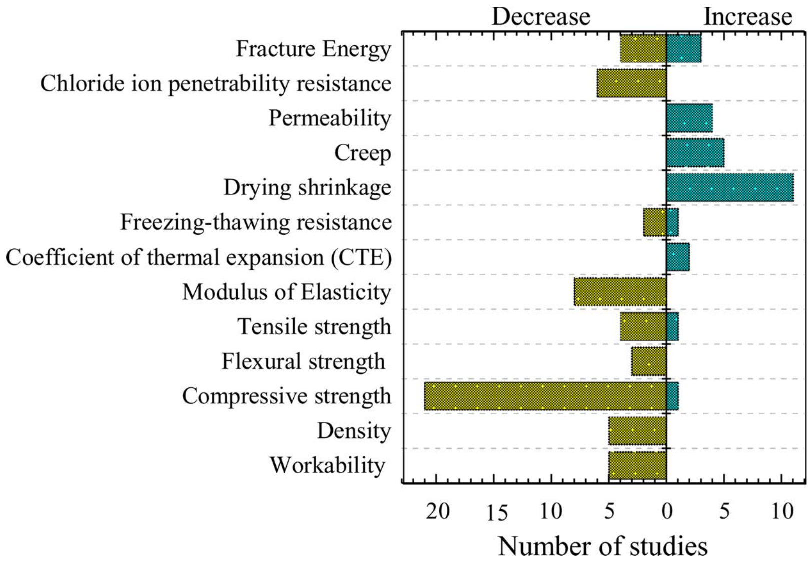

Fig. 13. Summarized influence of RCA on concrete properties.

(Arredondo-Rea et al., 2012; Khalil and Anwar, 2015). This is due to the pozzolanic reaction which reduces the pH (though the consumption of CH), make it favorable for carbonation to occur (Limbachiya et al., 2012). However, low pH also leads to depassivation of rebars and make it prone to corrosion. Moreover, as the secondary C-S-H formed and densified the concrete, the carbonation rate decreases (Limbachiya et al., 2012).

Several researchers have proven that the detrimental effects of RCA can be mitigated by using FA as partial OPC replacement (Verian, 2012; Verian et al., 2013; Smith, 2018; Verian et al., 2011b; Kurda et al., 2017b; Pürsünlü et al., 2013). Incorporating 20% of FA as the replacement of OPC was reported to improve the 28-day compressive strength of concrete made with 50% and 100% of coarse RCA by more than 10% and 5%, respectively (Verian, 2012). The Nernst-Plank chloride diffusion coefficients of 56-day old RCA concrete made with 100% coarse RCA are $2.66 \times 10^{-12}\,\mathrm{m^2/s}$ and $1.93 \times 10^{-12}\,\mathrm{m^2/s}$ for plain and concrete with 20% FA, respectively (Verian, 2012; Verian et al., 2013).

8.1.2. Ground granulated blast furnace slag (GGBFS)

GGBFS, also known as slag cement, possess latent hydraulic property which enhances the long-term durability properties of concrete (Wang et al., 2013; Li et al., 2012; Lübeck et al., 2012). Parthiban and Saravana Raja Mohan (2017) used a mix of sodium silicate (Na_2SiO_3, made of 28% SiO_2 and 11.2% of Na_2O) and sodium hydroxide (NaOH −99% purity) solution as the mixing liquid instead of water when they replaced all the OPC with GGBFS. This study incorporated coarse RCA at 0%, 25%, 50%, 75% and 100% for the mixture made with GGBFS binder. The use of GGBFS with the aforementioned activator has resulted in more superior quality concrete (higher compressive strength, flexural and split tensile strengths) at all aforementioned levels of RCA as compared to OPC concrete made with natural aggregate (Parthiban and Saravana Raja Mohan, 2017).

Another study by Majhi et al. (2018) used GGBFS with low activity index (grade 80 of ASTM C989) as up to 100% of OPC replacement. In addition to the GGBFS, this study also used up to 60% of coarse RCA (Majhi et al., 2018). Majhi et al. (2018) concluded that the mechanical properties i.e. compressive, split tensile and flexural strengths decrease as the percentage of RCA, GGBFS or both of these two increase. These results are contradictory with the study by Parthiban and Saravana Raja Mohan (2017). It needs to be noticed that in addition to use low-grade GGBFS, Majhi et al. (2018) did not use alkali activator in his study. Majhi et al. (Majhi et al., 2018) also increased the amount of water (up to $20\,\mathrm{kg/m^3}$) as the amount of GGBFS and RCA increased while Parthiban and Saravana Raja Mohan (2017) kept the amount of liquid constant for all concrete mixtures.

8.1.3. Silica fume (SF) and metakaolin

Kapoor et al. (2016) have proven that the use of SF and metakaolin as partial OPC replacements improves the properties of self-compacted concrete containing RCA. A study by Dilbas (2014) has indicated that SF improves the compressive strength of concrete containing RCA. Adding SF and metakaolin into RCA concrete mixtures improves the compressive strength and lowers the maximum hydration temperature (Radonjanin et al., 2013). Study results by Elhakam et al. (2012) have indicated that adding 10% of SF increases compressive and tensile strengths of concrete containing RCA. Dimitriou et al. (2018) have reported that adding FA and SF into RCA concrete mixture improved the durability properties significantly. Especially SF which found to reduce the permeability of RCA concrete (Dimitriou et al., 2018). The same study also reported that the mechanical properties of RCA concrete were not significantly influenced by FA and SF and low compressive strength was reported at the early age as the consequences of delayed pozzolanic activity by FA (Dimitriou et al., 2018). A study by Pedro et al. (2017) has indicated that incorporating SF in RCA concrete led to lower strength (up to 20% lower) at the early ages as compared to the control. However, the positive effect of SF was observed at later age as all the observed RCA concretes were able to achieve compressive strengths between 70 and 85 MPa after 91 days (Pedro et al., 2017). The same study also reported that SF led to lower tensile strength in RCA concrete (Pedro et al., 2017). Contradictorily, Çakır and Sofyanlı (2015) reported a continuous and significant improvement in the tensile strength of RCA concrete due to the presence of SF. Çakır and Sofyanlı (2015) also reported the reduction in the compressive strength at the early ages for NC and RCA concrete due to the incorporation of SF in the mixtures. However, this decrease was found to be less for RCA concrete as compared to the control (Çakır and Sofyanlı, 2015). Moreover, the same study also concluded that the use of SF is more effective on concrete made with 4/12 mm fraction of RCA than their counterpart which made of 8/22 mm RCA particles (Çakır and Sofyanlı, 2015).

8.2. Two-stage mixing approach (TSMA)

TSMA was developed by Tam et al. (2005); Tam and Tam (2007) to improve the quality of concrete made with RCA. In TSMA, mixing water was divided into two portions and was introduced to the concrete mixture at different times. In this mixing approach, all the aggregates are mixed for 60 s and then the first portion of water is introduced into the mixture of aggregates and the mixing continues for another 60 s. After 60 s of mixing the aggregates with the first portion of the water, cement is introduced into the mixture and the mixing process continues for 30 s. Later, the second portion of the water is introduced into the mixture and the mixing process continues for 120 s. Tam et al. (2005, 2007); Tam et al., 2005 has proven that this method improves the ITZ of concrete containing RCA. The drawback of this procedure is the longer mixing time as compared to the normal mixing approach (NMA) (270 s vs. 120 s). The schematic sequences for NMA and TSMA are shown in Fig. 14 (A) and (B) (Tam and Tam, 2007). The complete information regarding TSMA can be viewed in Ref. (Tam et al., 2005; Tam and Tam, 2007).

Some modifications of TSMA were also proposed by Tam and Tam (2007, 2008) which incorporates SF ($TSMA_S$) and a combination of SF with cement ($TSMA_{SC}$) in the pre-mix process. The schematic mixing sequences of $TSMA_S$ and $TSMA_{SC}$ are presented in Figs. 15 and 16, respectively (Tam and Tam, 2008).

According to Tam and Tam (2008), the use of $TSMA_S$ develops a denser old cement mortar by filling up the old pores and cracks with SF. The $TSMA_{SC}$ is found to further enhance the ITZ between RCA and cement paste since a certain amount of cement and SF are present, providing a stronger interfacial zone, and thus a higher compressive strength of RCA concrete. These results were confirmed by the laboratory testing results in which RCA concrete specimens made with $TSMA_{SC}$ method achieved a higher strength improvement in comparison with the specimens made with $TSMA_S$ method. The RCA concrete specimens prepared by using $TSMA_S$ and $TSMA_{SC}$ methods have superior performance than that of RCA concrete specimens made with conventional TSMA. These results indicate that $TSMA_S$ and $TSMA_{SC}$ are more effective than TSMA in enhancing the strength of RCA concrete (Tam and Tam, 2008). The illustration of the interface between RCA surfaces with concrete paste for NMA, $TSMA_S$, and $TSMA_{SC}$ are presented in Fig. 17.

8.3. Mortar mixing approach (MMA)

Mortar mixing approach (MMA) is developed by Liang et al. (2013) with the purpose to improve the fresh and hardened concrete properties. The schematic of MMA is presented in Fig. 18. All the coarse NA is replaced with coarse RCA. The coarse RCA underwent pre-surface treatment 7 days prior to the mixing. The improvement in compressive strength is reported on concrete made with 100% coarse RCA when MMA is applied as the mixing method.

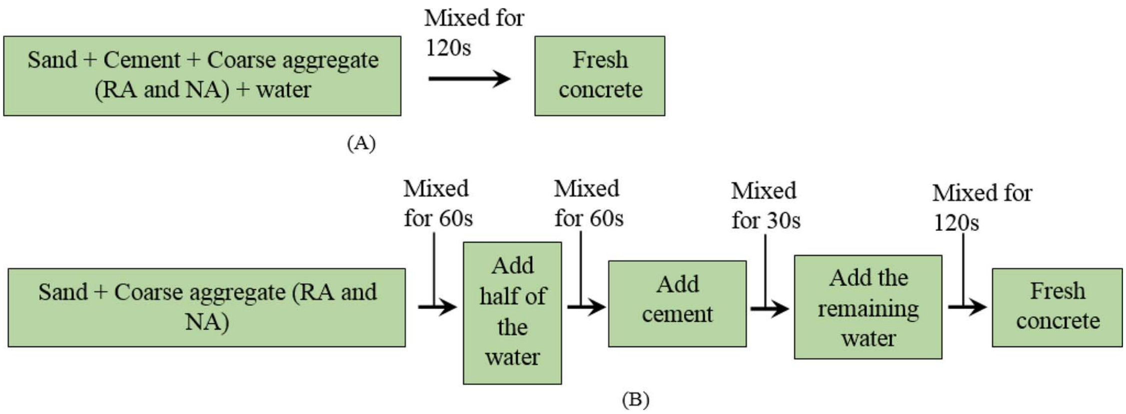

Fig. 14. Mixing sequences of the (A) Normal Mixing Approach–NMA and (B) Two-Stage Mixing Approach –adapted from Tam and Tam (2007).

8.4. Sand enveloped mixing approach (SEMA)

Sand enveloped mixing approach (SEMA) was also developed by Liang et al. (2013). Similar to MMA, the coarse RCA particles underwent pre-surface treatment 7 days prior to the mixing. RCA concrete made with this method had higher 28-day compressive strength as compared to that of RCA concrete made with MMA method and SEMA but without pre-surface treatment. This improvement is due to the formation of cement-SF solution which creates a coating layer on the surfaces of RCA (Liang et al., 2013). The concrete mixing sequence of SEMA method is shown in Fig. 19.

8.5. Reducing the mortar content on RCA

Reducing the mortar adhered to the RCA has shown improvement to the quality of the final product (ACI Committee, 2001). The mortar content of RCA can be reduced by crushing it into a smaller size and subsequent washing of the aggregates with water (e.g. crushing RCA with a maximum aggregate size of 25.4 mm (1 inch) into RCA with maximum size 19 mm (3/4 inch)) (ACI Committee, 2001). Katkhuda and Shatarat (2017) submerged the RCA for 24-h in 0.1 M hydrochloric acid (HCl) solution to remove the adhered mortar. This method is reported to successfully remove the old mortar as much as 0.76% and 0.54% of the total RCA mass for the 10 and 20 mm aggregates (Katkhuda and Shatarat, 2017). Parthiban and Saravana Raja Mohan (2017) adopted a method which was originally recommended by Akbarnezhad et al. (2011). In this method, attached mortar of RCA was removed by submerging the RA in a 2 M sulphuric acid solution for 5 days. The RA then was subsequently washed and sieved through #4 sieve (4.75 mm) to further separate the detached mortar from the aggregate. This method is reported to remove the adhered mortar as much as 12% to 20% of the initial mass of the RA. Skyrra Vassas Ltd., a local NA and RCA supplier in Cyprus, utilized a customized low-cost treatment to remove the adhered mortar on some of the RCA that was obtained by the company (Dimitriou et al., 2018). In this method, the RCA was placed into a modified concrete mixer which has a capacity of 8 m^3. The mixer was rotated at a speed of 10 rpm for 5 h. During this process, water was added to the rotating mixer to fully submerge the RCA particles. This washing process inside the rotating drum removes fine particles, dust and some of the adhered mortar. At the final step, the RCA was sieved in order to discard fine particles (< 4 mm). This process improved the quality of RCA substantially (Dimitriou et al., 2018).

8.6. Mixture design modification

Some studies have shown that modifying concrete's mixture proportion can compensate for the change in properties due to the use of RCA in concrete (Beltrán et al., 2014; Etxeberria et al., 2007). To offset the reduction in strength in concrete with RCA, additional cement can be added to the mixture while maintaining the same amount of water. For example, concrete made with 50% coarse RCA requires an addition of 6% cement to achieve the comparable compressive strength of NC (Etxeberria et al., 2007). When all the coarse aggregates were replaced by RCA, an additional 8.3% of cement is needed to maintain the compressive strength to be similar to that of NC (Etxeberria et al., 2007). Etxeberria et al. (2007) also showed that additional cement and admixtures are needed to improve the compressive strength and maintain the workability of concrete containing RCA. Mas et al. (2012) used Type III OPC to compensate the strength loss in RCA concrete. The guidelines for developing concrete mixture proportion using RCA can be found in Section 5.5.4–Removal and Reuse of Hardened Concrete, a technical report by ACI Committee (2001).

8.7. Limiting the amount of RCA in concrete mixture

To minimize the alteration of concrete properties due to the implementation of RCA, some researchers limit the amount of RCA used in the mixture. Kou et al. (2011) concluded that incorporating RCA up to 50% did not affect the compressive strength of concrete. A study by Verian has indicated that concrete pavement containing 30% of coarse RCA has similar to slightly better properties than NC (Verian, 2012). When class C FA is used as 20% replacement of OPC, the amount of coarse RCA can be increased up to 50% of the total coarse aggregate (Verian, 2012). Elhakam et al. (2012) conclude that the compressive strength of concrete is not affected when RCA is used up to 25% of total aggregates. Limbachiya et al. (2000) indicated that the addition of up to 30% of coarse RCA had no effect on the strength of concrete. Tam and Tam (2007) limited his study by using only up to 30% of coarse RCA as many researchers have suggested such limit.

8.8. Self-healing RCA

According to Gesoglu et al. (2015), self-healing RCA can be achieved by immersing the aggregates in water for 30 days. This procedure enables the unhydrated cement particles in the old mortar

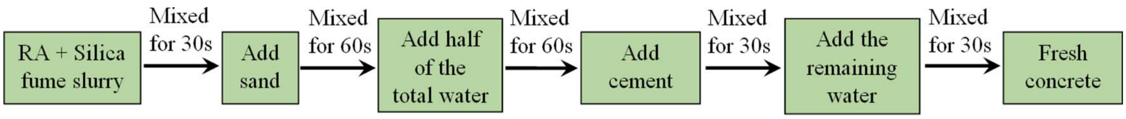

Fig. 15. TSMA with SF slurry– adapted from Tam and Tam (2008).

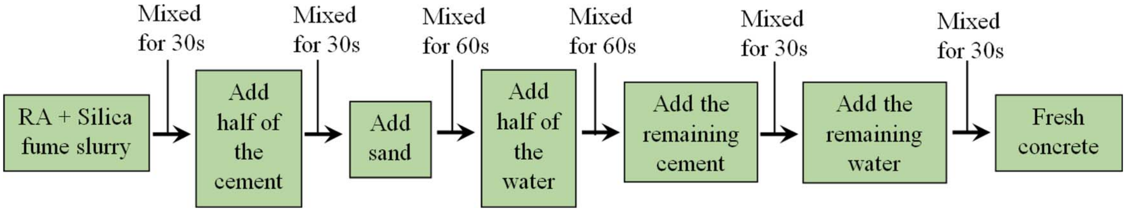

Fig. 16. TSMA with SFand cement slurry– adapted from Tam and Tam (2008).

adhered to the RCA particles to undergo hydration when it comes into contact with water (Gesoglu et al., 2015). This mechanism improves the quality of RCA as well as the quality of concrete incorporating these aggregates (Elhakam et al., 2012; Keskin et al., 2008; Zhong and Yao, 2008; Granger and Loukili, 2018; Qian et al., 2009).

8.9. Coating RCA surfaces with pozzolanic powder

Li et al. (2009) developed a new technique in which the RCA surfaces were coated with a mixture of pozzolanic powder (PP) (i.e. FA, SF, and blast furnace slag) and water. The schematic mixing process of this technique is presented in Fig. 20.

As it is shown in Fig. 20, the mixing process is initiated by creating a slurry of PP. This step is followed by introducing the RCA to the slurry. After a minute of mixing the RCA with the PP slurry, the remaining materials (the rest of the water, fine aggregate, and cement) are added to the mixer and mixed for another three minutes. The authors reported significant improvement in workability as the RCA concrete was mixed with this technique as compared to conventional mixing process. The hypothesis for the improvement in workability is due to the formation of the thin film layer made from PP which covers the surfaces of the RCA particles. This layer limits the absorbed water on RCA surfaces during the initial stage of mixing (Li et al., 2009). Moreover, this technique is claimed to improve the compressive and flexural strength of RCA concrete (Li et al., 2009).

8.10. Surface-modification technology

Choi et al. (Choi et al., 2016; Choi et al., 2014a; Choi et al., 2014b) developed a technique to improve the performance of low-quality RCA by covering the surfaces of RCA particles with a coarse paste containing inorganic admixtures. This method increases the compressive, tensile, and shear strengths of RCA concrete (Choi et al., 2016; Choi et al., 2014a; Choi et al., 2014b). The detail regarding surface-modification technology can be found in Ref. (Choi et al., 2016; Choi et al., 2014a; Choi et al., 2014b).

8.11. Using saturated aggregate

Several studies have indicated that saturating the RCA prior to the batching process improves the performance of the concrete (Brand et al., 2015; Leite and Monteiro, 2016; Pickel, 2014; Yildirim et al., 2015; Pickel et al., 2017). Fully saturating the RCA can be achieved by immersing the aggregate in the water for 24-h (Ferreira et al., 2011). According to Ferreira et al. (2011), 90% of saturation level was ideal while 100% of saturation level may have a detrimental effect on concrete. Etxeberria et al. (2007) wetted the coarse RCA used in their study and recommended a humidity level as high as 80% of the total RCA's absorption capacity to be achieved prior to its use in the batching process. This practice is reported to contribute to the controllable concrete quality in terms of the effective w/cm and the workability (Etxeberria et al., 2007). Moreover, a study on the microstructure of the recycled concrete by Leite and Monteiro (2016) indicated that the ITZ between the aggregate particle and the paste is denser for saturated RCA as compared to that of dry RCA. The higher absorption capacity of RCA as compared to NA provides a potential for supplying moisture from the aggregate's matrix to the bulk of the concrete. Despite its higher absorption capacity, the RCA used by Pickel et al. (2017) has insufficient desorption rate at 93% RH which limits the potential of RCA to provide internal curing. The benefit of using saturated RCA instead of dry is also reflected in the mortar where the compressive strength of the specimens made with saturated fine RCA is higher than its counterpart made with dry fine RCA Le et al. (2017).

8.12. Incorporating fiber into RCA concrete mixture

The use of fiber has been reported to offset some of the drawbacks from using RCA in concrete (Afroughsabet et al., 2017; Gao et al., 2017; Katkhuda and Shatarat, 2017). Katkhuda and Shatarat (2017) used up to six different levels (0%, 0.1%, 0.3%, 0.5%, 1% and 1.5% of the total volume of concrete) of basalt fiber (BF) on untreated and treated (24-h of submersion in 0.1 M of HCl solution) RCA. The study showed that concrete made with 20% of treated RCA (80% NA) with 1% and 1.5% BF yields higher splitting tensile and flexural strengths than that of control concrete (Katkhuda and Shatarat, 2017). These results are aligned with the study by Afroughsabet et al. (2017) which used 1% of double hooked-end (DHE) steel fiber in RCA concrete. Afroughsabet et al. (2017) reported that DHE steel fiber led to an up to 60% increase in the splitting tensile strength and up to 88% increase in the flexural strength of RCA concrete at 28 days. These improvements can be

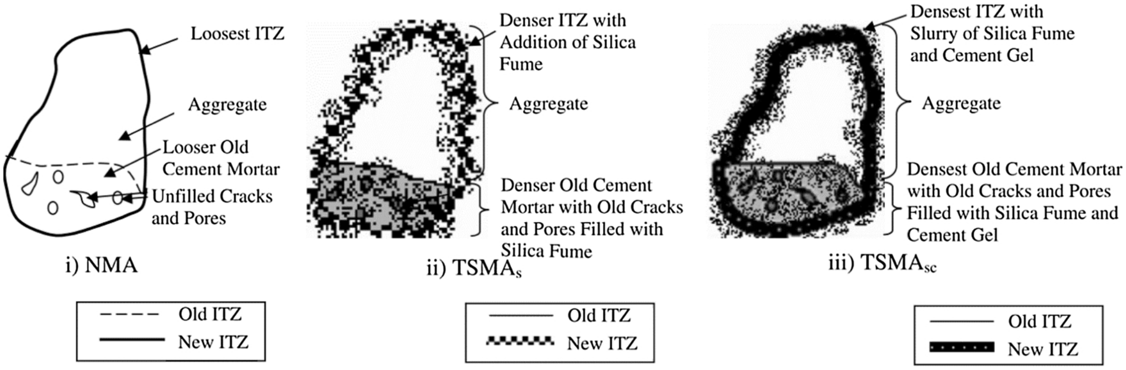

Fig. 17. The illustration of RCA particle structure after adopting (i) NMA, (ii) TSMA_{S}, and (iii) TSMA_{SC}– adapted from Tam and Tam (2008).

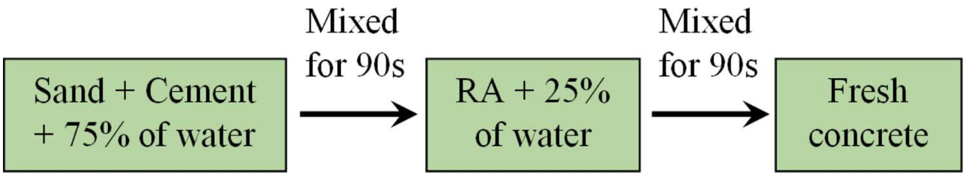

Fig. 18. The schematic of mortar mixing approach (MMA)– adapted from Liang et al. (2013).

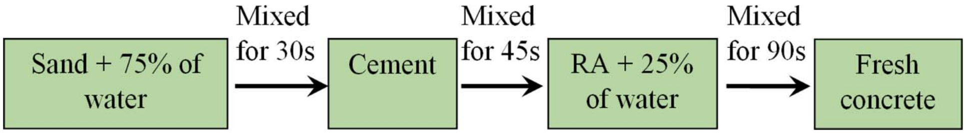

Fig. 19. The schematic of sand enveloped mixing approach (SEMA)–adapted from Liang et al. (2013).

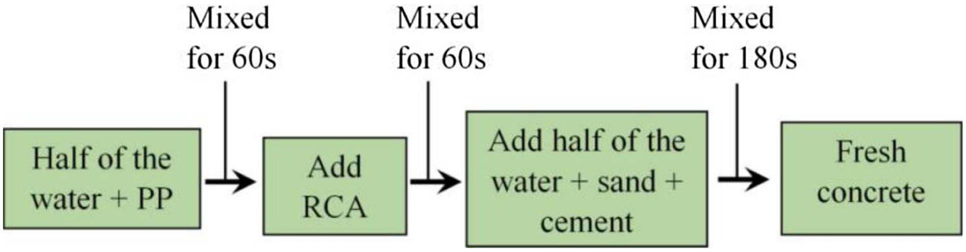

Fig. 20. The mixing process which incorporates RCA coating–adapted from Li et al. (2009).

attributed to the better bond between RCA and paste due to the rough surface of RCA in addition to the interlocking effect between the fibers and RCA (Afroughsabet et al., 2017). Gao et al. (2017) used up to 2% of steel fiber in his study which incorporated 30%, 50% and 100% of RCA. This study indicated that the presence of the steel fiber (up to 2% of the total volume) increased the shear strength (up to 135%) of the concrete containing 50% of coarse RCA (Gao et al., 2017). A study by Bordelon et al. (Bordelon et al., 2009) has indicated that incorporating synthetic macro-fibers as much as 0.2% of the total volume of concrete made with 50% coarse RCA improved its fracture properties into a level that is similar to NC.

9. Conclusions and recommendations

This section summarizes conclusions drawn from the study and provides general recommendations regarding the use of recycled aggregate (RCA) in the concrete mixture.

9.1. Conclusions

-The difference in properties of RCA with respect to NA is mainly driven by the presence of old mortars that adhere on the surfaces of RCA particles. This remnant of mortar responsible for the lower specific gravity, higher absorption, lower abrasion resistance of RCA as compared to NA.

-Assuring the quality of RCA (both fine and coarse) is crucial prior to its use as aggregate in the mixture in order to make a good quality concrete and/or mortar. One of the ways is by minimizing the amount of the attached old mortar on the surfaces of the coarse and/or fine RCA particles.

-The handling of RCA prior to the mixing process influences the quality of the batched concrete. Combined with proper mix design and batching process, the use of partially saturated to fully saturated RCA has shown to improve concrete performance relative to that of concrete batched with dry RCA.

-There are several ways to improve the quality of concrete containing RCA such as using saturated RCA, incorporating sufficient amounts of SCMs (i.e., FA, GGBFS, metakaolin and SF) in the mixture and performing other mixture-design modification (i.e. increasing the amount of cement, using superplasticizer to lower the w/b), coating RCA surfaces with PP, applying new ways of mixing concrete techniques (i.e., TSMA, $\mathrm{TSMA_S}$, $\mathrm{TSMA_{SC}}$, MMA, SEMA), surface-modification technology, self-healed the RCA prior to its usage in the concrete mixture, reducing the amount of old mortar and other impurities in RCA particles, incorporating fiber into RCA concrete mixture.

-The loss of workability when incorporating RCA in the concrete mixture can be addressed by several methods such as wetting the aggregate prior to the mixing, using plasticizer and/or a superplasticizer, incorporating SCMs as partial replacement of OPC and the combination of the aforementioned techniques.

9.2. Recommendations for use of RCA in concrete

Based on results of various studies by different researchers, several recommendations on the application of RCA in concrete are summarized as follows:

– To achieve good quality, the contaminants on RCA should be minimized. The removal of unwanted contaminants on RCA can be done by crushing RCA with the appropriate type of crushers (i.e. impact crusher and cone crusher) which are effective at removing the adhered mortar on the surfaces of the RCA (ACPA, 2010). Washing the RCA prior to the batching process is also recommended to minimize the amount of fine particles (minus #200 sieve/74 μm) and to reduce the potential of mixture workability problem associated to the moisture absorption during the mixing process (ACI Committee, 2001). Soaking the RCA in the 0.1 M of HCl solution is also an option for removing the old mortar from the RCA.
– The use of RCA in saturated condition is recommended to assure a better workability than using dry RCA. This effort can be combined with adding water reducing admixture into the mixture.
– There are no general limits on the use of coarse RCA in a concrete mixture. Several researchers recommend 30% as the maximum limit for using coarse RCA as replacement of coarse NA (Verian, 2012; Verian et al., 2013; Tam et al., 2005). This limit, however, can go even higher (i.e. 50%, 100%) if the mix design, batching methodology, and the moisture condition of the RCA are properly handled.
– Using modified batching techniques (i.e. TSMA, $\mathrm{TSMA_S}$, $\mathrm{TSMA_{SC}}$, MMA, SEMA) which have been proven to improve the quality of RCA concrete is recommended when incorporating this material into

concrete mixture.

- The use of SCMs (i.e. FA, GGBFS, SF and metakaolin) which have been proven to improve the quality of RCA concrete is recommended in RCA concrete (Verian et al., 2013; Verian et al., 2011a; Kou et al., 2007; Snyder, 2016; Kumar et al., 2017; Hansen, 1990; Silva et al., 2016b; Berndt, 2009).

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Appendix A

Table A1
Specific gravity of RCA and NA reported by different researchers.

Author	Specific gravity (gram/cc)	
	RCA	NA
Snyder et al. (1994)	2.10–2.40	2.40–2.90
Medina et al. (2014)	2.54–2.56	2.66
Gomez Soberon (2002), Poon et al. (2004)	2.35–2.42 (SSD) 2.17–2.28 (air dry)	2.59–2.67 (SSD) 2.57–2.64 (air dry)
Ann et al. (2008)	2.48	2.63
Xiao et al. (2005)	2.52	2.82
Fathifazl et al. (2009)	2.31–2.42 (bulk) 2.42–2.5 (SSD) 2.64 (apparent)	2.70–2.72 (bulk) 2.71–2.74 (SSD) 2.73–2.79 (apparent)
Kou et al. (2007)	2.49–2.57	2.62
Olorunsogo and Padayachee (2002)	2.60	2.61
Verian (2012), Verian et al. (2013)	2.3–2.33 (bulk) 2.42–2.45 (SSD) 2.62–2.66 (apparent)	2.62–2.69 (bulk) 2.69–2.74 (SSD) 2.82 (apparent)
Abbas et al. (2009)	2.31–2.42 (bulk) 2.42–2.5 (SSD) 2.64 (apparent)	2.7–2.72 (bulk) 2.71–2.74 (SSD) 2.73–2.79 (apparent)
Kapoor et al. (2016)	2.46	2.64
Evangelista and de Brito (2007)	1.91 (dry)* 2.17 (surface dry)*	2.54 (dry)* 2.56 (surface dry)*
Gesoglu et al. (2015)	2.10* 2.40	2.40* 2.70
Gokce et al. (2004)	2.41–2.5	2.64–2.65
Katz (2003)	2.23–2.25* 2.55–2.59	– –
Khatib (2005)	2.05–2.65	–
Lin et al. (2004)	2.11 (oven dry) 2.27 (SSD) 2.25 (SSD)*	2.62 (oven dry)* 2.68 (SSD) *
Limbachiya et al. (2000)	2.40–2.41 (SSD)	2.60
Sagoe-Crentsil et al. (2001)	2.39 (bulk)	2.89 (bulk)
Thomas et al. (2013)	2.32 (relative) 2.31 (SSD)	2.51–2.54 (relative) 2.55–2.59 (SSD)
Park et al. (2005)	2.34	2.55
Beltrán et al. (2014)	2.38 (SSD)	2.68 (SSD)
Zhihui et al. (2013)	2.65 (apparent)	2.73 (apparent)
Zaharieva et al. (2003)	2.16 ± 0.30 (dry density)* 2.25 ± 0.40 (dry density)	2.60 (dry density)* 2.68 ± 0.02 (dry density)
Corinaldesi and Moriconi (2009)	2.15 (SSD)* 2.32 (SSD)	2.62 (SSD)* 2.68 (SSD)
Rahal (2007)	2.39 (SSD) 2.31 (oven dry)	2.86 (SSD) 2.84 (oven dry)

(*continued on next page*)

Table A1 (*continued*)

Author	Specific gravity (gram/cc)	
	RCA	NA
Li (2009)	2.68 (SSD)	2.91 (SSD)
Vieira et al. (2016)	1.95* (dry density–recycled brick)	2.55* (dry density–coarse sand)
	2.97* (dry density–recycled sanitary ware)	2.53* (dry density–fine sand)
Salem et al. (2003)	2.40 (SSD)	2.67 (SSD)
Kurda et al. (2017a)	2.39 (oven dry)	2.63 (oven dry–coarse gravel)
	2.22* (oven dry)	2.74 (oven dry–gravel) 2.60* (oven dry–coarse sand) 2.59* (oven dry–fine sand)
Ait Mohamed Amer et al. (2016)	2.38 (specific weight)	2.63 (specific weight)
Pickel (2014), Pickel et al. (2017)	2.65 (apparent – RCA 1)	2.76 (apparent)
	2.70 (apparent – RCA 2)	
Roesler et al. (2013)	2.41 (bulk)	2.67-2.68 (bulk)
	2.20* (bulk)	2.57* (bulk)
Liu et al. (2011)	2.42 (apparent–RA20)	2.79 (apparent)
	2.43 (apparent–RA30)	

–: data not available
*: fine aggregate

Table A2
Absorption of RCA and NA reported by different researchers.

Author	Absorption (%)	
	RCA	NA
Snyder et al. (1994)	3.7–8.7	0.8–3.7
Medina et al. (2014)	4.36 – 4.49	2.66
Gomez Soberon (2002)	5.83–8.16	0.88–1.49
Poon et al. (2004)	6.28–7.56	1.24–1.25
Ann et al. (2008)	4.25	0.73
Xiao et al. (2005)	9.25	0.4
Kou et al. (2007)	3.52–4.26	1.11–1.12
Verian (2012)	5.3–5.4	1.8–2.7
Abbas et al. (2009)	3.3–5.4	0.34–0.89
Kapoor et al. (2016)	5.35	0.68
Evangelista and de Brito (2007)	13.1*	0.8*
Gesoglu et al. (2015)	10.9*	2.1*
	7.4	0.5
Gokce et al. (2004)	–	0.94
Katz (2003)	11.2–12.7*	–
	3.2–3.4	–
Khatib (2005)	0.5–14.75	–
Lin et al. (2004)	6.99	–
	11.9*	2.23*
Limbachiya et al. (2000)	4.9–5.2	2.5
Sagoe-Crentsil et al. (2001)	5.6	1
Thomas et al. (2013)	5.3	1.6–1.8
Park et al. (2005)	4.1	1.2
Beltrán et al. (2014)	6.94	1.53
Zhihui et al. (2013)	4.1	0.7
Zaharieva et al. (2003)	12.0 ± 1.5*	2.0*
	6.0 ± 0.5	0.2
Corinaldesi and Moriconi (2009)	10.0*	3.0*
	8.0	2.0
Rahal (2007)	3.47	0.68
Li (2009)	4.05	0.18
Ait Mohamed Amer et al. (2016)	5.05	0.96
Vieira et al. (2016)	12.63* (recycled brick)	0.58* (coarse sand)
	0.19* (recycled sanitary ware)	0.32* (fine sand)

(*continued on next page*)

Table A2 (*continued*)

Author	Absorption (%)	
	RCA	NA
Salem et al. (2003)	0.30	4.70
Kurda et al. (2017a)	5.0 (oven dry) 8.0* (oven dry)	1.4 (coarse gravel) 1.2 (fine gravel) 0.5* (coarse sand) 0.4* (fine sand)
Ait Mohamed Amer et al. (2016)	5.05	0.96
Pickel, 2014, Pickel et al. (2017)	4.72 (RCA 1) 6.93 (RCA 2)	1.53
Roesler et al. (2013)	5.51 9.85*	1.9–2.73 2.43*
Liu et al. (2011)	6.90 (RA20) 5.26 (RA30)	0.4

–: data not available
*: fine aggregate

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