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Recent Development and Perspective of Lightweight Aggregates Based Self-Compacting Concrete

T.Z.H. Ting, M.E.Rahman, H.H. Lau and M.Z.Y. Ting

Abstract

The utilization of natural and artificial lightweight aggregates in lightweight self-compacting concrete (LWSCC) is gaining popularity in research field. Extensive research has been carried out in the past decade all over the world to utilize lightweight aggregates (LWA) in self-compacting concrete (SCC). LWSCC, which uses renewable aggregates, has great potential to become an alternative material to conventional concrete. The paper is aimed to review the more recent research of physical properties of lightweight aggregates used in developing mix design of lightweight self-compacting concrete. In design, the mix proportion of LWSCC is a crucial factor to achieve the desired fresh and hardened concrete properties. The methods to develop LWSCC mix design with anticipated fresh and hardened concrete are reviewed. Research shows that the mix design LWSCC is preferably proportioned by aggregates packing concept. In addition, discussion on the fresh and hardened concrete properties is made and summarized in this paper. Studies indicate that there is a promising future for the use of lightweight aggregates in SCC as it shows satisfactory filling ability, passing ability, segregation resistance and compressive strength. Research gaps recommendations are then identified through this review to further discover lightweight self-compacting concrete in several aspects, particularly in term of sustainability.

Keywords: Lightweight self-compacting concrete (LWSCC), Lightweight aggregates (LWA), Workability, Compressive strength, Tensile Splitting strength

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1.0 Introduction

1.1 Concrete sustainability problem

Concrete is a very common construction material which has been widely used throughout the world due to its versatility, availability and economy (Rodriguez de Sensale et al., 2015). According to Samson et al. (2016), concrete is considered as the most heavily consumed construction materials in the world due to its low cost. The more recent statistics shows that there is more than 26.8 billion tonnes of normal concrete being produced globally per year (Senaratne et al., 2016). This huge production has caused the construction sector to face the issue of gradual exhaustion of natural resources as well as the difficulty in accessing them. In the aspect of the environmental impact of the concrete production, study shows that it can be reduced through the use of alternative materials (Mehta, 2001). The more common practice is the partial replacement of cement and aggregates alternatives.

Also for the reason of the high demand of concrete in construction industry, a large amount of normal weight aggregates (NWA) is consumed which has resulted in gradual depletion of natural gravel and crushed rock. The situation warrants the urgency to intensify the research and development of more sustainable construction materials. As such, great opportunity exists to incorporate construction and demolition wastes into concrete mix as aggregates in order to improve its resource productivity (Mehta, 2001). Research has been carried out for utilizing recycled aggregate from demolition waste (Duan & Poon, 2014; Etxeberria et al., 2007; Xiao et al., 2005). The recycle process involves stock piling, crushing, presizing, sorting, screening and contaminant elimination. However, processing of recycled aggregates requires large amount of energy and cause higher carbon dioxide emission. Alternatively, other materials such as lightweight aggregates (LWA), either arising naturally or being generated as by-product from industrial processing, can be used to replace NWA in the concrete production. This leads to the production of lightweight concrete (LWC). LWC is commonly produced by replacing the

normal weight aggregates with LWA. Extensive research has been carried out to utilize the waste generated as alternative construction materials in concrete due to growing of sustainability consciousness. (Alengaram et al., 2013; Aslam et al., 2016)

1.2 Lightweight self-compacting concrete

With the advancement of concrete technology, several attempts have been made in developing new high performance materials that possess the benefits and characteristics of SCC and LWC in the past decades. An innovative concrete, lightweight self-compacting concrete (LWSCC), which possesses the properties of both LWC and SCC has been developed. LWSCC is produced by the replacement of NWA with LWA in SCC. According to ACI 213 (2014), the density of structural lightweight concrete must falls within the range of 1120 kg/m³ to 1920 kg/m³. Aggregates contribute to the most of the weight of concrete and commonly constitute about 60% by volume of SCC (Topçu & Uygunoğlu, 2010). As such, due to the porous structure of LWA, it is able to reduce the density as well as the thermal conductivity of concrete. The use of LWSCC brings about several benefits such as reduced self-weight, shorter construction period, lower construction cost and elimination of noise emitted from vibration machines as well as better heat and sound insulation due to the voids in LWA (Grabois et al., 2016; Papanicolaou & Kaffetzakis, 2010; Vakhshouri & Nejadi, 2016). Since the present construction industry is experiencing the shortage of skilled workers as well as the difficulty in hiring new generation of skilled workers (Kim et al., 2010), LWSCC which is less labour intensive, can be a timely solution to these shortcomings. In addition, LWSCC, which is very suitable for manufacturing precast units, can be used to promote mechanisation or even automation processes in construction industry. The assembly of precast building components units on site has made the construction methods more straightforward.

1.3 Application of lightweight self-compacting concrete

LWSCC has been employed as alternative construction materials in structural construction such as cable stayed bridge construction since 1992 in Japan (Ohno et al., 1993). Dymond (2007) had designed and constructed a 20m pre-stressed beam by using LWSCC while Lahkega and Stenah (2011) studied the possibility of utilizing LWSCC in full scale wall. Also, Shi and Yang (2005) had utilized LWSCC in the application of thin precast C-shaped wall. Hubertova and Hela (2007) made use of LWSCC in the construction of stadium walkway structural elements. Lately, the use of LWSCC has become popular in construction and research field.

1.4 Type of lightweight aggregates

Lightweight aggregates can generally be categorized into natural and artificial types. The common natural LWA are pumice, diatomite, volcanic cinders, scoria and tuff (ACI-213, 2003; Neville, 2008). As for the artificial LWA, it can be further categorized into industrial wastes and processed natural materials (Aslam et al., 2016). Sintered slate, sintered pulverized fuel ash, expanded or foamed blast furnace slag and colliery wastes are more common industrial wastes used as LWAs. In addition, there are also processed natural materials such as shale, expanded clay, slate, vermiculite and perlite which can be used as LWA in manufacturing concrete (Mahmud, 2010). Numerous researches have been concentrated on utilizing artificial LWA in developing LWSCC.

1.5 Problems in lightweight self-compacting concrete

There are several common issues in developing mix design of LWSCC. As LWA is porous materials and generally irregular in shape, its workability is poor and compressive strength is relatively low when compared to gravels. As such, a large amount of cement paste is required for LWSCC to achieve desired workability and targeted compressive strength. Due to the porous structure of LWA, it has high water absorption capacity which tends to absorb the water during batching, resulting in poor workability. The high water absorption of LWA makes it

difficult to estimate the required water volume for batching. The common practice to overcome this issue is to allow LWA to achieve saturated surface dry (SSD) condition before batching (Domagała, 2015). However, care must be taken since different type of LWA has different water absorption rate. Excessive water can increase the risk of bleeding and segregation (Illidge, 2010; Juradin et al., 2012). Moreover, the densities of lightweight aggregates are generally lower than those of the mortar matrix and natural aggregates in concrete (Topçu & Uygunoğlu, 2010). Therefore, the difference in density between LWA and normal weight sand can alter the fresh properties of LWSCC mixture. The resulting poor self-compaction and segregation of aggregates can severely affect the durability and structural performance of concrete in hardened state (Juradin et al., 2012; Kwasny et al., 2012). Thus, the use of LWA in SCC is still regarded as new development in concrete technology and further investigation and study are required. In addition, no code of practice or guideline has been published for developing mix design of LWSCC.

1.6 Objective

As LWSCC brings about advantages in many aspects, research to understand the complicated nature of LWSCC is gaining popularity. Therefore, the main objective of this paper is to review the lightweight aggregates (LWA) that have been used in developing lightweight self-compacting concrete. Identification of the physical properties as well as comparisons of LWA are conducted. In addition, the effect of using LWA in SCC mixture on fresh and hardened concrete properties will be discussed. The methodology to develop LWSCC mix design is reviewed too. In summary, the LWSCC properties and mix design can be improved significantly upon the review of the currently available literature.

2.0 Lightweight aggregates

Extensive research has been carried out by many researchers in utilizing lightweight aggregates (LWA) in SCC. Hwang and Hung (2005) utilized reservoir fine sediment as coarse aggregates

in SCC while Bogas et al. (2012) and Hubertová and Hela (2013) studied the possibility of expanded clay as coarse aggregates. Pumice has been used as lightweight coarse aggregates and studied by several researchers under different temperature and mix proportioning (Özge Andiç-Çakır & Hızal, 2012; Kaffetzakis & Papanicolaou, 2012; Papanicolaou & Kaffetzakis, 2010; Tayfun Uygunoğlu & Topçu, 2009). Also, Shi and Wu (2005) and Lo et al. (2007) have utilized expanded shale as LWA for SCC. Moreover, Kanadasan and Razak (2014) used agriculture waste, palm oil clinker, as aggregates in SCC. The physical properties of the selected lightweight aggregates including pumice, expanded shale and expanded clay will be discussed in the following part of the paper. The fresh and hardened state properties of LWSCC are highly depends on the physical properties of LWA used. In this connection, specific gravity, size distribution, shape thickness and texture, bulk density and water absorption characteristic of lightweight aggregates will be elaborated.

2.1 Specific gravity

Specific gravity is defined as the ratio of the material mass to the mass of an equal volume of water at the temperature of 23°C. Based on the research done by several researchers, all the three types of lightweight aggregate (LWA) have different values of specific gravity which are not more than specific gravity of normal weight aggregates of 2.4-2.9. The specific gravity values of all these three types of aggregate falls within the range of 0.42-2.25 as shown in Table 1.

The specific gravity for pumice aggregates is within the range of 0.69-2.25. Özge Andiç-Çakır and Hızal (2012) reported the lowest specific gravity of pumice aggregates is 0.69 while Tayfun Uygunoğlu and Topçu (2009) reported the highest specific gravity of 2.25. For expanded shale aggregates, the specific gravity values are in the range of 1.33-1.35 which are considerably consistent. Expanded clay aggregates have the specific gravity of 0.42-1.78. Gopi et al. (2015) found the lowest specific gravity of 0.42 of expended clay aggregates while Shanker (2016)

found the highest of 1.75. This inconsistency of specific gravity may be due to the situation whereby the aggregates are supplied from different sources as well as the different ways they are processed in the industry. By comparing the LWA and NWA (shown in Table 1), the specific gravity of LWA is 10% to 80% less than that of NWA. Aggregate specific gravity is important in the calculation of weight-to-volume relationships and to compute various volume-related quantities such as voids presented in aggregate, and that the voids that must be filled by cementitious materials. It affects the resulting workability and final density of designed LWSCC.

2.2 Size Distribution of LWA

Lightweight aggregates (LWA) generally occur in different particle shape and size. Sieve analysis or gradation test is a common method for determining the particle size distribution. The particle size distribution of LWA is crucial in engineering application as it can be used to verify the compliance of design requirement, production control and specifications. Typical particle size distribution curves of pumice, expanded shale and expanded clay are shown in Figure 1 (Lotfy et al., 2016; Topçu & Uygunoğlu, 2010). It is noted that pumice aggregates possess better particle distribution curve than expanded shale and expanded clay aggregates. The use of well graded aggregates in SCC will minimize the voids which leads to optimum workability and strength. As such, selection of appropriate size distribution of aggregates is important in designing LWSCC mix design.

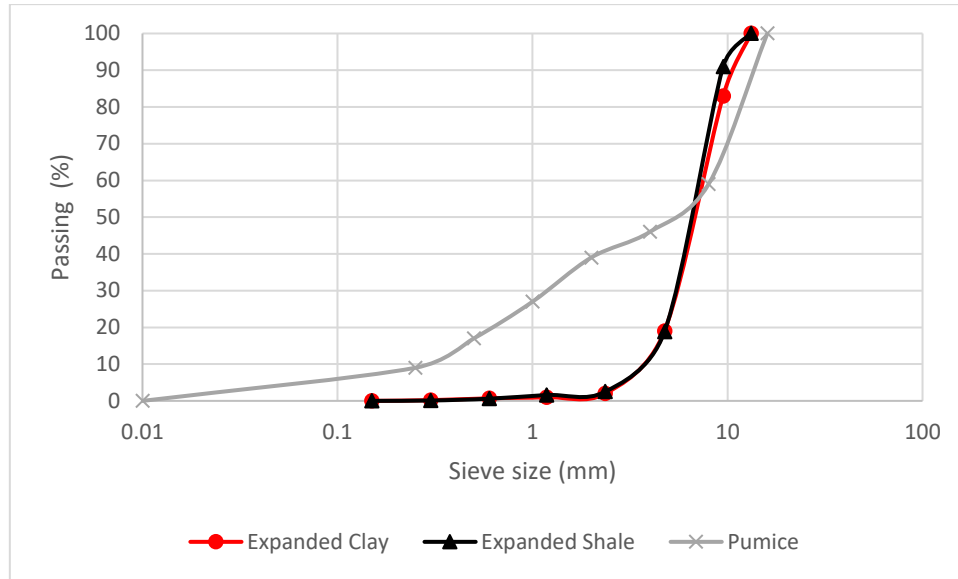


Figure 1: Particle size distribution of LWA (Lotfy et al., 2016; Topçu & Uygunoğlu, 2010).

2.3 Shape thickness and texture

According to Tviksta (2000), the performance of SCC is very sensitive to the characteristics of aggregates. These characteristics include shape, texture, maximum size, grading and morphology. The shape and size of coarse aggregates have significant influence on the particle packing and aggregate interlocking within the matrix. They are factors in determining the amount of paste volume to cover all particles. LWAs commonly exist in angular and flaky shape. Khaleel et al. (2011) had studied the effect of maximum aggregate size on flowability of SCC. The authors found that the flowability of SCC decreased with the increase of coarse aggregate size. The authors also recommended the use of coarse aggregates with maximum 10mm size as it can produce higher strength SCC than that produced by using coarse aggregates of maximum 20mm size. From the review of LWA of several researchers as summarized in Table 1, most of the coarse LWA maximum size used in LWSCC is either 12.5mm or 16mm. This is to promote a good interlocking effect between them to enhance the packing characteristics and flowability of SCC which will guarantee the strength of concrete (Kanadasan & Razak, 2014).

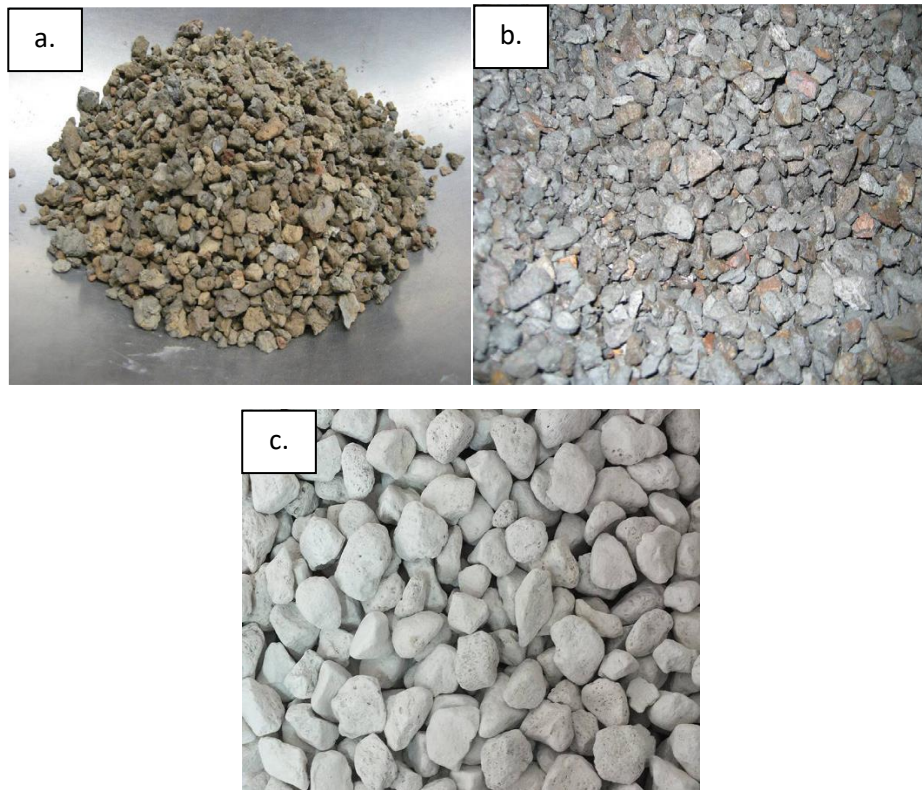


Figure 2: Lightweight aggregates: a) Expanded clay, b) Expanded shale, c) Pumice (Lotfy et al., 2016)

2.4 Bulk density

Bulk density of aggregates measures the volume of their solid aggregate particles as well as the voids between them that they occupy in the concrete. The bulk density is used in the volume method of concrete mix proportioning. Many researchers did not provide the compacted bulk density of the LWA aggregates used. As shown in Table 1, the loose bulk density of LWA from different sources generally shows variation. The bulk density of expanded clay, expanded shale and pumice aggregates is in the range of $300\text{--}1280\text{ kg/m}^3$, $750\text{--}1500\text{ kg/m}^3$ and $330\text{--}1010\text{ kg/m}^3$ respectively. Ahmad et al. (2007) stated that aggregates with density within the range $700\text{--}1400\text{ kg/m}^3$ are preferable for structural application. By comparison, the bulk densities of all these three LWA are 10-80% lesser than normal weight aggregates. The lightweight characteristic of LWA is generally due to its porous characteristics.

2.5 Water absorption

LWA are generally porous materials which tend to absorb water. LWA will absorb and hold more moisture than normal weight aggregates. As a result, pre-wetting of LWA is required before batching and this practice has been used in manufacturing lightweight concrete (LWC). Depending on the cellular structure of LWA, it may also take longer time to achieve saturated surface dry (SSD) condition (Peters, 1999). The 24-hour water absorption of these three aggregates is in the range of 5-80%. By comparing these three LWA, pumice is found to have the highest water absorption capacity. LWSCC is sensitive to the water content of LWA as it can alter the resulting workability and compressive strength of concrete. The water/binder ratio of concrete can also be affected by the water absorption of LWA (Liu et al., 2011). The water absorption capacity of LWA must be specified in order to maintain the consistency of LWSCC. According to Shafigh et al. (2012), concrete with porous aggregates is less sensitive to poor curing as the strength may vary only 6-11%. This is due to the fact that the water present in aggregate pores is capable of providing internal curing. The sensitivity can be reduced when lower water/binder ratio is used. The water present in aggregates is able to reduce plastic shrinkage due to unfavourable drying condition and provide internal curing which allows for more complete hydration of cement (Pierce, 2007).

Table 1: Physical properties of lightweight aggregates (LWA).

Pumice aggregates					
Researchers	Size of aggregates (mm)	Specific gravity	Loose bulk density(kg/m^3)	Compacted bulk density(kg/m^3)	24h water absorption (%)
Kaffetzakis and Papanicolaou (2016a)	8-16	-	570	1034	-
Kaffetzakis and	8-16	-	-	-	25

Papanicolaou (2012)					
Özge Andiç-Çakır and Hızal (2012)	4-16	0.69-1.74	330-1010	350-1105	8.25-45.62
Topçu and Uygunoğlu (2010)	4-16	1.84	-	739	28.75
Kurt, Kotan, et al. (2016)	16	0.92	-	-	-
Kurt et al. (2015)	16	0.92	-	-	-
T. Uygunoğlu and Topçu (2011)	16	1.84	-	739	28.75
Kaffetzakis and Papanicolaou (2016b)	4-16	-	580	1050	25
Anwar et al. (2012)	19	1.13	-	-	84.57
ö Andiç-çakır et al. (2009)	4-8 8-16	-	440	480	25
Kurt, Gül, et al. (2016)	16	0.92	-	-	-
Tayfun Uygunoğlu and Topçu (2009)	16	2.25	739	-	29
Expanded shale aggregates					
Researchers	Size of aggregates (mm)	Specific gravity	Loose bulk density	Compacted bulk density	24h water absorption (%)
Lotfy et al. (2015b)	4.75-12	1.33	862	-	14
Lachemi et al. (2008)	10	1.35	754.6	-	5.4

Lo et al. (2007)	10	-	1490	-	4 (1hour)
(Lotfy et al., 2015a)	10	1.33	862	-	14
Wu et al. (2009)	20	-	-	-	4
Shi and Wu (2005)	-	-	-	-	-
Karahan et al. (2012)	12	-	-	-	-
Lotfy et al. (2016)	4.75-10	1.33	862	-	14
Expanded clay aggregates (LECA)					
Researchers	Size of aggregates (mm)	Specific gravity	Loose bulk density	Compacted bulk density	24h water absorption (%)
Lotfy et al. (2016)	4.75-10	1.21	621.5	-	16.2
Gopi et al. (2015)	-	0.42	442	-	39
Abdelaziz (2010)	15	1.08	667	-	20.07
Kwasny et al. (2012)	4-8	-	1280	-	15
Grabois et al. (2016)	12.5	-	956	-	13.95
Floyd et al. (2015)	12.5	1.25	-	-	15
Juradin et al. (2012)	1-8	-	-	-	-
Lotfy et al. (2014)	12	1.21	621.5	-	16.2
Cui et al. (2010)	5-10	-	670	1175	9.2 (1h)
Lotfy et al. (2015a)	10	1.21	621.5		16.2

Maghsoudi et al. (2011)	4.75-9.5	-	-	-	18.02
Rajamanickam and Vaiyapuri (2016)	12	0.42	-	-	38
Bogas et al. (2012)	12.5	-	613	1068	12.3
Mohammadi et al. (2015)	-	0.45	300	-	40
Corinaldesi and Moriconi (2015)	15	1.15	-	-	15
Shanker (2016)	12	1.78	-	1112	40

2.6 Remark

The mix proportion of LWSCC and its corresponding performance in terms of both fresh and hardened state are greatly dependent on the physical properties of LWA incorporated. Concerning the characteristics of LWA such as specific gravity, size gradation, shape, texture, and water absorption capacity, they can significantly alter the amount of material used in mix design. Specific gravity of LWA used can affect the resulting concrete density. From the review above, it is noted that the specific gravity of LWA of less than 2.0 is used to produce lightweight concrete in order to produce concrete of density below 1920kg/m^3 . Aggregate size, gradation and texture can greatly influence the amount of cement paste used to lubricate aggregates in order to achieve self-compacting ability as well as to fill in the voids between aggregates. Since LWA is generally present as angular and flaky shape, most of the researchers have limited the maximum coarse aggregates size up to 12.5 or 16mm. This can reduce the surface-to-volume ratio in order to minimize the cement used to achieve better workability and hence lower cost. Moreover, the water absorption of LWA can greatly affect both fresh and hardened properties. High water absorption LWA can cause workability loss when it is used as dry condition during

batching. Saturated LWA can greatly alter the water to cementitious material ratio used which will result in poor compressive strength of concrete. In the light of considerable influence of water absorption of LWA, LWA must be pre-wetted and allowed to achieve saturated surface dry (SDD) condition in order to prevent either water loss or high water content before batching.

3.0 Mix design of LWSCC

The mix proportions of LWSCC are crucial in its application as the selected proportions can affect the required properties in fresh and hardened states. Similar to SCC, LWSCC must attain the desired fresh properties such as filling ability, passing ability and segregation resistance so as to fulfil the self-compacting requirement. Filling ability, which is also known as flow ability, is the capability of concrete to flow and fill the formwork completely under its own weight. Meanwhile, passing ability refers to the capability to flow past the confined spaces between steel reinforcement congested area without segregating and clogging within the space of formworks. Segregation resistance is the capability to stay homogeneous during the process of transporting, placing and after placing without tendency to bleed and separation of aggregates from mortar. Similar to any other type of concrete, strength, volume stability and durability of the hardened LWSCC are important in structural applications (Sethy et al., 2016). The performance of LWSCC is greatly influenced by the constituent of raw materials, the dosage of chemical and mineral admixtures, types of aggregate used, packing density, water to cement ratio (W/C) and design procedures.

At the present moment, standardized method for obtaining mix design of SCC does not exist. Many researchers have developed and proposed several design methods for SCC based on scientific theories and empirical expressions. In the context of SCC, the design methods can be classified into five categories based on their design principles, which are empirical design method, compressive strength method, close aggregate packing method, statistical factorial

method and rheology of paste model (Shi et al., 2015). However, there is limited mix design method has been developed for LWSCC. The majority of the available LWSCC mix design methods in literatures are mainly based on close aggregate packing method. Many researchers prefer to develop the mix design of LWSCC by trial and error method as most of the proposed methods are not suitable to be used once the requirement of application is changed. This is commonly done by varying the binder content, binder/water ratio, admixture dosage, fine and coarse aggregate ratio. The review of LWSCC mix design method will be presented in the following section.

3.1 Shi and Wu Method

The combination of the least void volume for binary aggregate mixture, excess paste theory and ACI 211 has been adopted by Shi and Wu (2005) in proportioning the mix design of LWSCC. The relationship between void volume or density of combined aggregates and coarse to fine aggregates volume ratio is determined by using particle packing concept in accordance with ASTM C29/ C29M. The least void volume of combined aggregates was found to be 0.5 in their study. However, the authors recommended to use coarse to fine aggregates ratio of 0.6 as it does not increase much void but decrease the density significantly. Excess paste theory is then used to determine the minimum quantity of paste required to fill in the void among the aggregates and also to allow SCC to flow with minimum frictions between aggregates as well as to balance the mixture by the quantity of water retained by the aggregates as illustrated in Figure 3. The required volume of excess paste is highly dependent on the characteristics of LWA, such as gradation, shape and surface texture, which can be determined through laboratory tests. The cement content and water to cement ratio are then determined from ACI 211 based on the designed compressive strength. The cement content is fixed from the chosen value while excess paste is produced from powders including fly ash and glass powder. The workability is then adjusted by varying the SP dosage. The authors successfully design LWSCC with

satisfactory flowability and segregation resistance by using the proposed method. However, the proposed method requires intensive laboratory work to obtain the necessary information to proportion mix design.

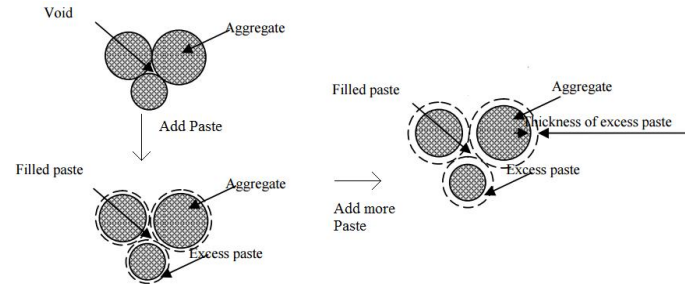


Figure 3: Excess Paste Theory (Abdizadeh et al., 2009)

3.2 Hwang and Hung method

For DMDA, Hwang and Hung (2005) developed this method based on ACI 318 and the fact that high physical density can produce optimum physical properties. In DMDA method, the mixture proportion algorithm is classified into aggregate and paste phase. Aggregate phase comprises lightweight aggregate, normal weight fine aggregate and fly ash while cement, slag, water and superplasticizer constitute paste phase. Finer particles fill the voids of the coarse aggregates to minimize the porosity in order to form the major skeleton of aggregates phase as shown in Figure 4. This in turn increases the density of solid materials and reduces the content of cement paste as illustrated in Figure 5. Paste phase is mainly used for lubricating aggregates in order to achieve concrete workability. This method is suitable for mix proportion design aimed to reduce water and cement content by using the physical packing density of aggregate which results in lower permeability of LWSCC. Though, this method does not take into account the optimum weight of concrete as long as the optimum properties are obtained. This may result in high density concrete. The authors recommended to use high water to binder (w/b) ratio of more than 0.42 to prevent autogenous shrinkage of the cement paste due to cement hydration and pozzolanic reaction. In fact, it is not necessary to use high w/b ratio when LWA are pre-

soaked and achieved saturated surface dry condition (SSD) before casting. The water from internal pores is able to prevent the autogenous shrinkage. Moreover, in this method, the aggregates packing density can be enhanced by adding fly ash which fill the voids in LWA. Fly ash should not be considered as the part of aggregate phase as fly ash is supplementary cementitious materials.

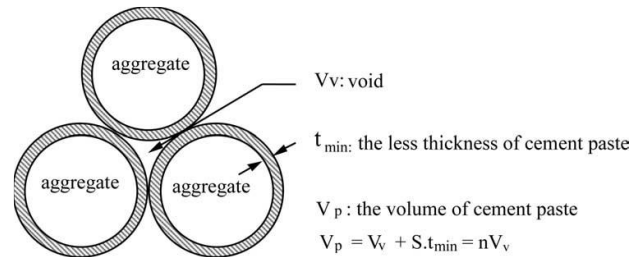


Figure 4: DMDA method(Hwang & Hung, 2005).

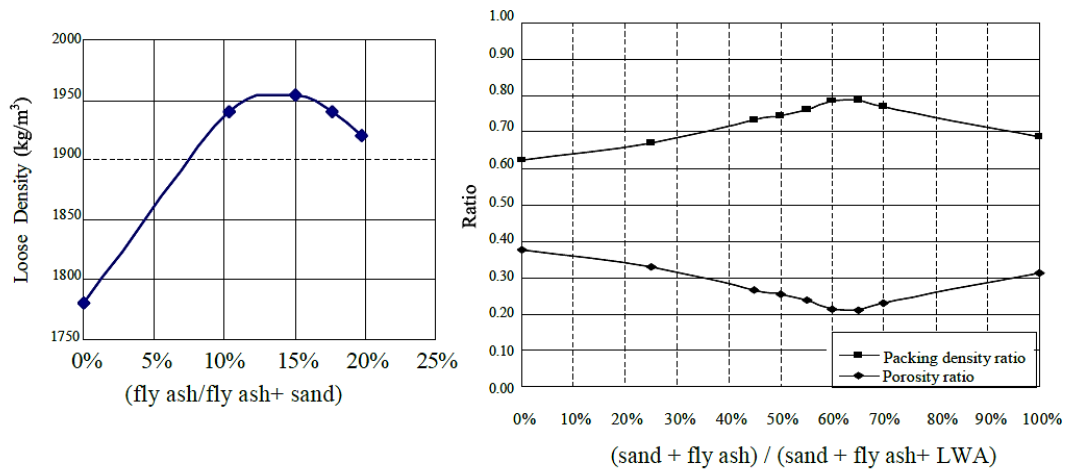


Figure 5: Packing density and porosity of concrete mix (Hwang & Hung, 2005).

3.3 Kaffetzakis and Papanicolaou

Kaffetzakis and Papanicolaou (2012) proposed another LWSCC mix design method based on optimum packing point (OPP) concept and workability criteria. This method involves the investigation of paste, mortar and concrete phase of material. Cement paste and mortar are assessed through wet packing method, which is used to determine the packing density of cement paste and mortar. This concept involves the determination of total voids and air voids as well

as the solid concentration factor of a given water to cementitious materials volumetric ratio (V_w/V_{cm}). High V_w/V_{cm} ratio is used as trial initially. The ratio is then decreased until solid concentration factor is about to decrease. Void ratio versus V_w/V_{cm} curve will be plotted based on the trials as shown in Figure 6 . Optimum packing and void ratio can be determined from the curve. The derived mortars from OPP concept must be assessed for self-compactness through slump-flow and V-funnel test. This method assumes that the least void volume of mixture corresponds to the optimum flowability in both paste and mortar. For concrete phase, the aggregate packing index is first determined from aggregate apparent and particle density. LWSCC is then proportioned by modifying the mortar to aggregates void volumetric ratio based on the equation derived by Jacobsen and Arntsen (2008). The workability must be assessed using SCC fresh concrete test. The authors argue that maximizing packing density should be solely used to determine the mix proportion of LWSCC, which contradicts with the method proposed by Hwang and Hung (2005).

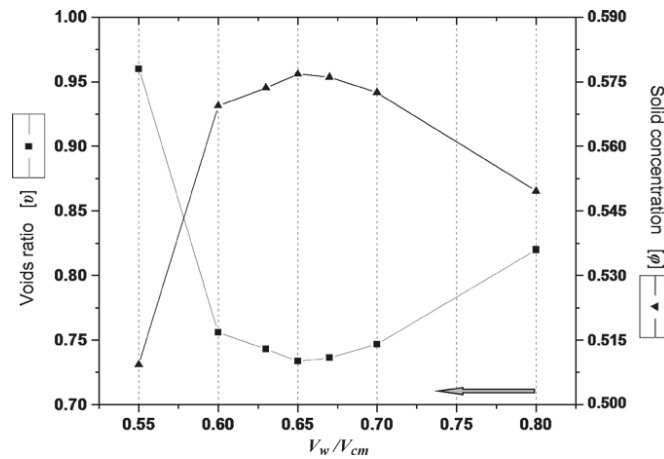


Figure 6: Total voids versus V_w/V_{cm} (Kaffetzakis & Papanicolaou, 2012)

Kaffetzakis and Papanicolaou (2016b) proposed a semi-automated mix design methodology which was based on the concept of optimum packing point (OPP) from their previous research and incorporated with statistical analysis. The authors derived a series of procedures from statistical analysis and previous research works to proportion the LWSCC mix design based on

the target performance. Three performance parameters, which are 28-day compressive strength ($f_{lcm.cube}$), oven-dry density (ρ) and slump flow (S-F), can be pre-set in the equations from the statistical analysis in order to determine the required mix proportion. Design parameters including volumetric ratio of LWA (V_{la}), water to cementitious material ratio (W_{ef}/CM) and cementitious material content (CM) can be calculated based on the design performances and equations proposed by Kaffetzakis and Papanicolaou (2016a). These procedures involve the specifying the desired performance, calculation of design parameters and implementation of OPP procedures as illustrated in Figure 7. The authors have validated the design procedure by carrying out two LWSCC mix designs and the resulting performance correlates well with the proposed target. However, this method is only limited to the use of certain materials such as cement, limestone fillers, silica fume and pumice aggregates. Further laboratory investigation as stated in previous research (Kaffetzakis & Papanicolaou, 2012) has to be carried out if other materials are used in producing LWSCC.

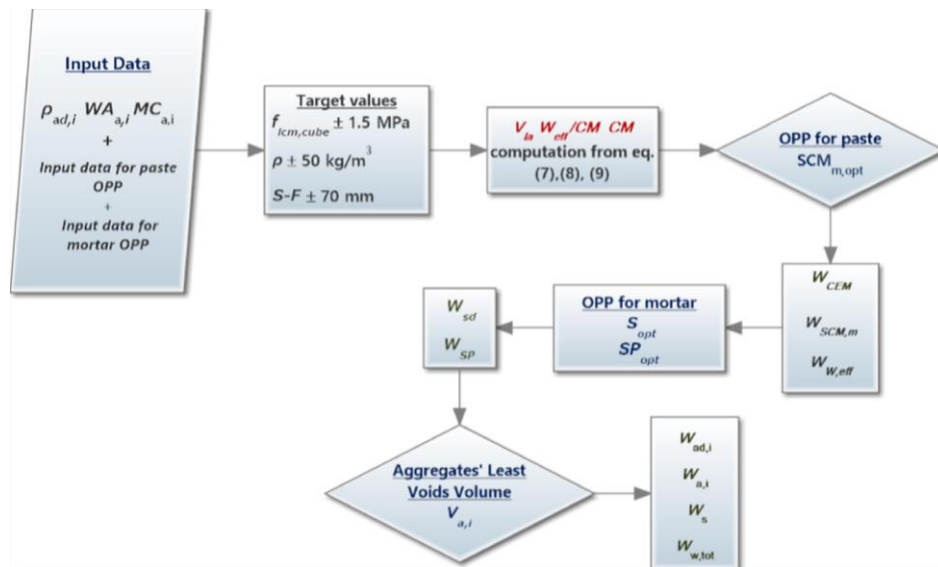


Figure 7: Semi-automated LWSCC mix design procedure(Kaffetzakis & Papanicolaou, 2016a)

3.4 Kanadasan and Razak method

Kanadasan and Razak (2014) modified the particle packing method of SCC which was originally proposed by Choi et al. (2006) to allow for the substitution of palm oil clinker (POC) aggregates in SCC. The substitution can be made on either fine or coarse aggregates at the level of 0% to 100%. It is based on the concept of minimizing the void of concrete by using appropriate size and gradation of aggregate with the use of minimum volume of paste as shown in Figure 8. The authors introduced an additional correction lubrication factor (LCF) to particle packing factor (PP) to allow for the characteristics of LWA aggregates when aggregates substitution is made in LWSCC mix design. The authors highlighted that the voids produced by flaky and porous structure of POC aggregates could be filled and lubricated by the binder paste. The proposed method fixed the fine aggregates ratio at 0.5 and 0.6 to allow wider range of ratios for SCC. The authors studied the cement content varied from 380 to 420kg/m³ and recommended that 420kg/m³ could produce the optimum performance SCC. However, the authors also mentioned that trial has to be carried out to ensure the required performance. The authors also demonstrated experimentally that the proposed method is able to produce LWSCC when 100% substitution of LWA is incorporated. PP theory is able to produce LWSCC mix design with minimum void volumes relative to the coarse aggregate, water to binder ratio, maximum cementitious materials density as well as the optimum fresh concrete properties. This theory provides good understanding of the consumption of aggregate and paste volume for a given unit volume of concrete. The proposed method is also applicable for a variety combination of other aggregates. However, the PP factor and CLF have to be determined in laboratory if other types of aggregates and their combinations are used. Besides, the actual performances of the designed mix must be checked in laboratory.

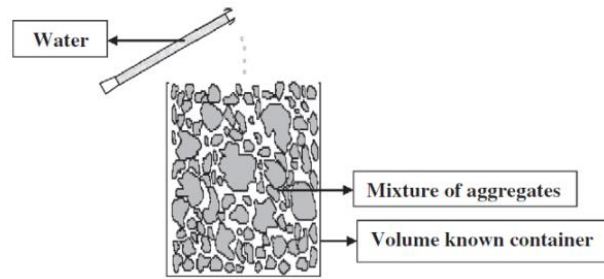


Figure 8: PP Test Illustration (Kanadasan & Razak, 2014).

3.5 Li et al. method

Li et al. (2017) proposed another LWSCC mix design method based on the packing and mortar film thickness theory. This method determines the sufficient amount of paste to fill the voids between aggregates and form a thin layer to overcome the frictions between aggregates which is similar to the DMDA proposed by Hwang and Hung (2005). The methodology involved two stages, which are the optimization of granular skeleton of aggregates and cementitious material composition. Stage one involves the characterization of coarse and fine aggregates in terms of bulk density and void volume percentage. The authors adopted the method proposed by Shi and Wu (2005) to obtain the optimum balance point between bulk density or porosity of aggregates and coarse aggregates to total aggregates ratio (V_g/V_{Total}). The authors recommended to use coarse to total aggregates ratio of 0.6. The value higher than 0.6 could result in more consumption of paste to fill the void in LWA which could lead to more production cost. A value less than 0.6 will result in higher density which contradicts to the definition of lightweight concrete. These values are then used to determine the optimum coarse to fine aggregates volume ratio with the consideration of mortar film thickness (MFT). MFT is defined as half the average distance between surfaces of coarse aggregate particle. It reflects the dosage and physical properties of coarse aggregates including aggregate grading and stacking porosity. Stage two involves the optimization of minimum water content required for binder by using the method proposed by Laboratory Central des Ponts et Chaussées (LCPC). Cement, mineral admixtures water and filler dosage are then determined based on the minimum water and the respective

material density. The amount of SP dosage needs to be determined through the rheology study of mortar in laboratory. Trial batch must be carried out to ensure the mix design can achieve the required performance. The authors highlighted that the mixing time should not more than 3 minutes to avoid segregation. The authors suggested an equation to estimate the dry density of LWSCC mixture from the proposed design as below:

$$\rho_{\text{dry}} = m_s + m_g + 1.2m_{\text{cm}}$$

where m_s is the mass of sand; m_g is the mass of coarse aggregates; and m_{cm} is the mass of cementitious materials. From the results of validation tests, the authors stated that interfacial transition zone (ITZ) between aggregates and paste can be improved and more compacted due to the increase of MFT. The authors have successfully developed the LWSCC mix design with adequate fresh properties and compressive strength up to 54MPa by using the proposed methodology. In short, the proposed method is based on simple design principles and is applicable to other type of LWA. However, the proposed method is not able to proportion the LWSCC mix design based on specified workability and compressive strength criteria.

3.6 Nepomuceno et al. method

Nepomuceno et al. (2018) modified a normal weight SCC mix design method which was originally proposed by their previous research (Nepomuceno et al., 2012; Nepomuceno et al., 2016; Nepomuceno et al., 2014) to develop LWSCC mix design. The proposed methodology is based on the rheological study of mortar phase and combination of it with coarse aggregates in concrete phase. This methodology involves the characterization of constituent materials, determination of volumetric ratio of both fine aggregates and coarse aggregates from reference grading curve which was originally proposed by Nepomuceno et al. (2014), and powder material to total volume of respective content. Volume ratio of water to power content and mass

ratio of superplasticizer to powder content are then determined in mortar phase through iterative process experimentally until flow capacity and fluidity complied to the required rheology. The volume of LWA is then determined by quantifying the ratio between the volume of mortar and coarse aggregates and finally the volume of void is defined based on the porosity of LWA. In this method, the effect of low density of LWA was considered by adding extra criteria in mortar rheological study stage. The flow properties in mortar phase must be able to prevent the dynamic and static segregation of LWA. The authors stated that the dynamic segregation resistance can be evaluated during workability test while static segregation is evaluated by visual observation of axially cut cylinders after 24h of batching. The authors noticed that the reference grading curve of NWA is applicable to LWA since the LWA used in their research has more round and spherical shape compared to NWA. However, the reference grading curve must be determined in laboratory by using the method proposed by if LWA of different shape index is used. LWSCC can be proportioned based on the required fresh and hardened properties such passing ability, density and compressive strength. The passing ability of designed LWSCC can also be quantified by V_m/V_g ratio by using the statistical equation proposed by Nepomuceno et al. (2014) and Nepomuceno et al. (2016). The density of designed mix is highly dependent on V_m/V_g ratio and can be considered in the equation of this proposed method. The designed compressive strength of LWSCC can be quantified by varying W/C ratio and V_m/V_g ratio through the statistical equation or design chart provided. The authors have successfully developed the LWSCC mix design with adequate fresh properties and compressive strength in the range of 35 to 59MPa by using the proposed methodology. In short, compared to the methodology proposed by other researchers, this method is able to proportion the LWSCC mix design based on selected passing ability, density and compressive strength requirements.

3.7 Remark

Although Mazaheripour et al. (2011) recommended to apply high performance concrete mix design method for LWSCC to avoid segregation and maintain the strength, the method cannot produce optimum LWSCC mix proportion in terms of fresh and hardened properties. The resulting density is not within the upper limit of lightweight concrete in accordance to ASTM. It is clear from the research reviewed above that most of the proposed methodologies for proportioning LWSCC mix design are based on close aggregate packing principle. Aggregates packing principle is used to determine the least void among the aggregates in order to minimize the void produced by LWA as well as to determine the optimum coarse to fine aggregates ratio in order to produce the lowest density LWSCC. From the literatures above, it is noticed that the coarse to fine aggregates ratio used is generally in the range of 0.5 to 0.6 and the ratio of 0.6 is recommended by most of the researchers as it is the most cost efficient. The paste is then applied to fill the voids to become LWSCC which can be determined through either excess paste theory or rheological study of cement paste or mortar. However, intensive laboratory work is required in obtaining the necessary information. Most of the proposed methodologies is not able to proportion the LWSCC mix design based on required performance such as specified workability and compressive strength criteria. Furthermore, durability requirements such as shrinkage, creep, physical durability and chemical durability are not considered in proposed mix design methodology by researchers. As such, further statistical data analysis is required in order to simplify and produce performance based LWSCC mix design methodology.

4.0 Fresh Properties of LWSCC

4.1 LWSCC workability criteria

As previously stated, LWSCC must be assessed for filling ability, passing ability and segregation resistance and they are used to measure the workability of LWSCC. There are several methods for assessing each of these properties. Several publications such as EFNARC

(2002) and ACI-237 (2007) provide the guidelines to carry out workability test for SCC. The methods to assess the filling ability are slump flow, T_{500} , Kajama box, v-funnel, o-funnel and orimet. Assessing the filling ability is the most fundamental test for any type of SCC as it can be used to assess the consistency of SCC to meet the guideline requirements. The test for assessing passing ability are L-box, U-box, J-ring and Kajama box. These tests adopt the concepts of allowing SCC to pass through a pre-set spacing. This spacing is the smallest gap whereby SCC can flow continuously to fill the formwork. Also, segregation resistance can be assessed through penetration, sieve segregation, settlement column and visual segregation. SCC is mostly prone to segregation during and after placing. Segregation is a crucial problem in the casting of vertically tall structural element as it can lead to the uneven distribution of aggregates and mortar in LWSCC. The workability performance requirements of EFNARC (2002) for SCC are shown in Table 2. According to EFNARC (2002), these criteria are developed based on the current knowledge and research. SCC with fresh properties outside these criteria may be acceptable if it is able to perform properly under the required conditions. Future developments will likely produce different requirements for these criteria. For example, these criteria may be relaxed if the formwork design is very simple or the spacing between the reinforcement is large.

Table 2: SCC workability criteria of EFNARC (2002) guidelines

Workability	Test	Class	Criteria
Filling ability	Slump Flow (mm)	SF1	550-650
		SF2	660-750
		SF3	760-850
	T500 (s)	VS1/VF1	≤ 2 V – Funnel ≤ 8
		VS2/VF2	≥ 2 time(s) 9 – 25
Passing ability	Step height in J-ring (mm)	PA1	$S_j \leq 15$ (59 mm bar spacing)
		PA2	$S_j \leq 15$ (40 mm bar spacing)
	L-Box		0.8 - 0.1

	U-Box		0 - 30
Segregation Resistance	Sieve segregation (%)	SR1	≤ 20
		SR2	≤ 15

4.2 Review of previous research

In the past decade, substantial study has been done on the fresh and hardened properties of LWSCC.. Lotfy et al. (2015a) had studied LWSCC with different type of LWA including furnace slag, expanded clay and expanded shale. The authors found that LWSCC with expanded shale as LWA achieved the best workability with respect to filling ability, passing ability and segregation resistance among the three aggregates. Lotfy et al. (2015a) explained that the fine portion of expanded shale aggregates is finer than the other two LWA which results in better packing density and less void between the aggregates particle, allowing the excess paste in LWSCC to achieve better flowability and segregation resistance. The excess paste required for improving workability highly depends on the gradation, shape and surface texture of aggregates. They agreed the research outcome of Shi and Wu (2005). In short, the workability of LWSCC is highly dependent on the aggregates packing density and void volume.

Lotfy et al. (2015b) performed a series of experimental investigation on the parameters that affect the workability of LWSCC. They studied the effect of water to binder ratio (w/b), superplasticizer dosage and total binder content on the workability of LWSCC. Expanded shale was used as aggregates in LWSCC. From their research outcome, the filling ability and passing ability of LWSCC were found to be improved significantly with the increasing of w/b ratio and superplasticizer dosage respectively as well as the combination of these two parameters. The improved parameters are indicated by the increasing spread of slump flow, reduction of v-funnel flow time and increasing of L-box ratio. However, with the fixed amount of superplasticizer, there is a limit to the improvement of the filling ability of LWSCC by increasing the content of binder. The increase in binder content resulted in higher demand of

superplasticizer so as to maintain similar filling ability. Similarly, the increase in water and superplasticizer dosage was found to be able to improve the passing ability. However, the increase in binder content would affect the passing ability negatively. In contrast, segregation resistance was found to be improved with the increase of binder content as it can enhance the packing density of LWSCC mixture. Nonetheless, poor segregation resistance was resulted as water and superplasticizer dosage increased. They agreed with the research findings of Sonebi et al. (2007) that the fresh properties of SCC are significantly affected by water and superplasticizer dosage. LWSCC exhibit similar behaviour as the normal SCC when influenced by water and superplasticizer dosage. In general, the performance of LWSCC workability with respect to filling ability, passing ability and segregation resistance is greatly influenced by water to binder ratio, superplasticizer dosage and total binder content.

Grabois et al. (2016) investigated the effect of steel fibers on the fresh and hardened properties of LWSCC. Expanded clay was used as aggregates in their research. The addition of steel fibers in LWSCC was able to slightly increase the slump flow spread. It is because steel fibers, which have higher density, provide more self-weight for SCC to flow under gravity. However, the V-funnel flow time decreased with the addition of steel fibers due to the blockage of steel fibers inside the V-funnel restricted area. They demonstrated that the LWSCC with poor flow time were able to be used for casting the “U”-shape thin wall panel. The aggregates and fibers were found to be homogenously distributed along the panel length. The findings in their study provided a new understanding that LWSCC is able to fill the narrow formwork even with the flow time outside the SCC workability requirement as stated in Table 2.

On the other hand, Mohammadi et al. (2015) examined the effect of silica fume with 0% to 15% of binder replacement on the properties of LWSCC workability with expanded clay and perlite as aggregates. The flowability and segregation resistance of LWSCC were found to be improved with the replacement as well as the increased dosage of silica fume. They also

concluded that LWSCC with expanded clay as aggregates achieved better workability compared to LWSCC with perlite as aggregates.

Corinaldesi and Moriconi (2015) studied the effect of the addition of synthetic fibers in LWSCC with expanded clay as aggregates and recycled concrete aggregate as partial replacement. It was noticed that the incorporation of fibers is able to improve the filling ability while it had negative effect on the passing ability. Silica fume was also studied. They observed that addition of small amount of silica fume can result in higher viscosity. Poor flow ability and passing ability were observed but the segregation resistance was improved. Similar observation was obtained with addition of silica fume in LWSCC with synthetic fibers. However, the findings of Corinaldesi and Moriconi (2015) had contradicted with the findings obtained by Mohammadi et al. (2015).

A comprehensive study of LWSCC was done by Floyd et al. (2015) on the effect of cementitious material and aggregate type on the workability of LWSCC. Two types of aggregates, which are expanded clay and expanded shale, were studied by them. They found that better visual stability of LWSCC was achieved by increasing the cement content. For common finding similar with other researchers, the increase in superplasticizer dosage could result in improved filling and flowing ability. With the constant amount of SP dosage and w/b ratio, the increase of volumetric sand to total aggregate ratio was found to be able to produce better fresh properties with optimum ratio of 0.51. Also, no significant improvement in fresh properties was noted by incorporation of silica fume with 5% and 10% in LWSCC with lower cement content. For LWSCC with high cement content, the fresh properties tend to be improved with only 5% or 10% incorporation. Poorer fresh properties were achieved by LWSCC with Type I cement compared to Type III cement. The fresh properties of LWSCC with Type III cement can be improved by partially replacing binder with fly ash as shown in their study. Floyd et al. (2015) stated that LWSCC with expanded shale exhibited better fresh properties compared to expanded clay with the same amount of other mixture content which agreed with the findings

of Lotfy et al. (2015a). Also, the authors changed the coarse aggregates distribution in their study by limiting the maximum aggregate size to 12.5mm. This resulted in better fresh properties. In short, the fresh properties of LWSCC are highly dependent on binder content, SP dosage, type of aggregates used and volumetric sand to total aggregate ratio.

Kurt et al. (2015) investigated the effect of fly ash, different water to binder ratio and replacement of pumice aggregates with natural aggregates on LWSCC. The filling ability was found to be improved with the increasing of water to binder ratio as well as fly ash replacement. Due to the low pozzolanic activities of fly ash, its increase could retard the bonding of water to mixture and hence the loss of workability. However, segregation was observed in their research when water to binder ratio exceeded the optimum value. Also, the spreading capability of slump flow was found to be increased with the density increase of LWSCC as the spread and placement properties of LWSCC were highly dependent on its own weight. With the increase of pumice aggregates in LWSCC, the time required to spread 50cm diameter also increased as well as the V-funnel flow time. This can be explained by the loss of weight with the replacement of LWA in LWSCC resulted in self-weight to be less than threshold stress. Since the self-weight was below the threshold stress, the authors implied that it could increase the tendency of static segregation.

Bozkurta and Taşkin (2017) studied the effect of the use of barite, fly ash and pumice as powder on the LWSCC fresh properties. The authors observed that LWSCC with barite powders are the best among three types of powder in improving the fresh properties in terms of flowability and filling ability. However, the authors reported that the use of barite as powder content in LWSCC could cause bleeding due to its poor adhesiveness and viscosity resistance. As such, the ratio of low adhesive powder content is crucial in developing LWSCC to prevent bleeding.

Ardalan et al. (2017) investigated the effect of fly ash, pumice and slag as binder partial replacement in LWSCC on retention workability after 50minutes. The authors stated that pumice blend require more superplasticizer dosage to achieve target slump flow among the three types of supplementary cementitious materials. Conversely, fly ash blend requires lesser dosage of SP in order to achieve target slump flow. It was explained that the spherical geometry of fly ash particles is able to reduce the friction resistance of cement particles and enhancement of the mixture fluidity. Among the three types of blend mixture, fly ash blended LWSCC showed significant slump flow loss after 50minutes while pumice blended LWSCC showed the best retention capacity.

Law et al. (2018) studied the LWSCC incorporated with perlite, scoria and polystyrene (BTS) as lightweight aggregates. LWSCC with BTS are highly prone to segregation due to their ultra-lightweight characteristic. This can be overcome by using higher binder content which could provide sufficient plastic viscosity to suspend the aggregates in concrete. The passing ability of LWSCC with scoria aggregates decreased with increasing scoria aggregates replacement. The authors recommended to improve the passing ability by increasing the binder content. The author concluded that the use of lightweight aggregates at high level replacement to produce LWSCC could result in adverse effect on workability. Meanwhile, Aslani et al. (2018) studied the effect of partial replacement of scoria and recycled aggregates in LWSCC. Their mix designs are similar to that of Law et al. (2018). The authors reported that although recycled aggregates contribute negative influence on workability of LWSCC, the combination of recycled aggregates and scoria aggregates are still able to produce LWSCC that fulfill the criteria of EFNARC (2002).

4.3 Remark

The studies presented thus far provide evidence that the workability of LWSCC is highly dependent on the aggregates packing density and void volume. In general, similar to normal

SCC, the performance of LWSCC workability with respect to filling ability, passing ability and segregation resistance is greatly influenced by water to binder ratio, superplasticizer dosage and total binder content. The inclusion of different types of supplementary materials has different effects on LWSCC workability. When silica fume is used, and with increasing replacement level, the segregation resistance of LWSCC is found to be improved while it has negative effect on filling and passing ability. The inclusion of fly ash as binary or ternary blend can not only improve all the three fresh properties but also reduce the amount of SP required. In addition, the incorporation of fibers such as steel and synthetic fibers is able to improve the filling ability but it causes negative effect on passing ability.

5.0 Hardened properties of LWSCC

5.1 Compressive strength

The most important required property of any innovative material is its compressive strength. The compressive strength of concrete has great influence on its structural performance. As mentioned previously, the compressive strength of LWSCC is significantly affected by the composition of raw materials, the dosage of chemical and mineral admixtures, types of aggregate used, packing density and water to binder ratio (W/B).

Substantial research has been done on the compressive strength of LWSCC with different parameters. Corinaldesi and Moriconi (2015) studied the effect of addition of synthetic fibers in LWSCC with expanded clay as aggregates and recycled concrete aggregate as partial replacement. In their research, low density LWSCC (1250kg/m^3) with concrete strength of grade 40 at 28 days could be achieved by the addition of silica fume which could enhance the concrete strength development. According to the authors, the addition of macrofibers did not compromise the degree of concrete compaction of which even could result in more viscous concrete. However, the compression strength was found to be 10% higher than LWSCC without fibers. Similar trends of LWSCC compression strength were obtained by using steel fibers or synthetic fibers at high dosage. The addition of fibres such as steel, synthetic and macro fibers will increase the compressive strength of LWSCC.

Lotfy et al. (2015a) conducted a series of study on the hardened properties of LWSCC by using different type of LWA such as furnace slag, expanded clay and expanded shale. The volume ratio of coarse to fine aggregate of all the mixtures were determined by particle packing procedures in accordance with ASTM C29/C29M. They had found that LWSCC with expanded shale as LWA achieved the highest strength and expanded clay attained the lowest among the three types of LWA. The authors explained that these were attributed to the lower volume of coarse LWA for LWSCC with expanded shale. Expanded shale aggregates achieved superior

packing density which reduce the coarse portion required and enable more fine particles to fill up the voids in the concrete matrix. Lotfy et al. (2015a) suggested that higher strength LWSCC can be proportioned with relatively low dry density, high aggregate packing density and low coarse to total aggregates volume ratio. The authors also noticed that aggregates are the weak point of the concrete matrix in LWSCC as all the failed samples exhibited aggregate fracture. It is also proven by the studies of Nepomuceno et al. (2018). The authors reported that LWSCC attained lower compressive strength when compared to normal SCC with the same mix proportion. LWSCC achieved compressive strength between 35-57MPa while SCC achieved 53-87MPa. As pointed out by these researchers, under compressive force, LWSCC fail with the rupture of LWA as they form the weak link in the concrete matrix.

Lotfy et al. (2015b) performed a series of experimental investigation on the parameters that affect the hardened properties of LWSCC. The w/b ratio and total binder content were found to be the main parameters affecting the LWSCC compressive strength. The LWSCC strength increased with the decreasing of w/b ratio. The 28-day compressive strength also increased with the increase of total binder content. The amount of superplasticizer dosage was found to have no effect on the LWSCC strength. These findings conformed to the basic knowledge of concrete property.

Grabois et al. (2016) observed that their LWSCC mix design were able to achieve 70% of the 28-day strength in a day. Their mix design is suitable for high early strength applications. Also, the incorporation of steel fibers in LWSCC could result in lower compressive strength. For failure mode, they noticed that the rupture was occurred through the LWA and yet the interfacial transition zone was still intact. The authors explained that the mortar was stronger than LWA in lightweight concrete which was in conformity with the findings of Lotfy et al. (2015a). The use of expanded clay aggregates could result in better paste-porous LWA bonding.

Mohammadi et al. (2015) studied the effect of silica fume on LWSCC containing perlite and expanded clay as LWA. They observed that the LWSCC containing expanded clay as LWA achieved higher compressive strength compared to perlite as LWA. However, the compressive strength differences decreased when the increase of silica fume replacement. The replacement of silica fume in LWSCC would increase LWSCC compressive strength. Nevertheless, Mohammadi et al. (2015) only studied the silica fume replacement up to 20% of total binder. The result is yet to be known if the silica fume replacement is more than 20%. The optimum replacement percentage is also not known.

Kurt et al. (2015) conducted a series of experimental test to investigate the effect of fly ash, different water to binder ratio and replacement of pumice aggregates with natural aggregates on LWSCC. With the increasing percentage of pumice aggregates replacement, the compressive strength of LWSCC decreased significantly. This concurred with the findings of Floyd et al. (2015) and Grabois et al. (2016) that the LWA are generally weaker than mortar even though the LWA used by both authors are different. Also, Kurt et al. (2015) found the compressive strength decreased with higher water content which is generally true. LWSCC with fly ash replacement gain strength at the slower rate than that those without fly ash replacement at the early stage (e.g. 7 days). Nevertheless, they achieved almost similar strength at later age (e.g. 90 days). The authors attributed the findings to low pozzolanic activity of fly ash at the early stage when its content increased. The replacement of fly ash in LWSCC could significantly improve the fresh concrete properties but require longer time to gain strength.

A comprehensive study was done by Floyd et al. (2015) to investigate the effect of cementitious material and aggregates type on the properties of LWSCC. The LWSCC with expanded clay were found to fail around the aggregate particle while LWSCC with expanded shale failed with the fracture of individual particles. The authors explained that the smooth surface of expanded shale aggregates had caused poor bonding between the aggregates and cement mortar. From

the failure mode of LWSCC with expanded clay, Floyd et al. (2015) concluded that the compressive strength of LWSCC is greatly influenced by the strength of LWA. The authors also found that water to binder ratio has less significant effect on compressive strength of LWSCC designed with high cement content in their particular research. The authors also observed that it was difficult to estimate the moisture content of wet LWA before concrete casting. The moisture content can cause significant variation in compressive strength of LWSCC with the given amount of cement content and w/b ratio.

Ardalan et al. (2017) studied the compressive strength of LWSCC with different types of supplementary cementitious material including fly ash, slag, pumice and silica fume in binary and ternary blend. The authors stated that the use of fly ash and pumice at high level replacement could result in significant strength reduction. However, slag with high level replacement showed comparable strength to control mix. Ternary blend of cement, pumice and silica fume resulted in increased compressive strength when compared to control mix. The author also noticed that increasing of silica fume content could significantly improve the compressive strength at 28 days.

Law et al. (2018) studied the compressive strength of LWSCC incorporated with perlite, scoria and polystyrene (BTS) as lightweight aggregates. Increase in LWA content in LWSCC could result in decrease in compressive strength. Among the three types of LWA, scoria based LWSCC showed less significantly strength reduction when the LWA content was increased. The authors reported that the use of BTS in LWSCC could result in weak bond between the binder paste and the aggregates, thereby creating a weak interfacial transition zone and hence reduction in compressive strength. Perlite based LWSCC showed most significant strength loss when the LWA content was increased. The authors explained the excess pore water in the perlite was released due to crushing during mixing.

5.2 Flexural strength

Flexural strength is one of the parameters measuring the tensile strength of concrete. No significant improvement on the flexural strength of LWSCC with the addition of synthetic fibers was noticed in the works of Corinaldesi and Moriconi (2015). In the research done by Lotfy et al. (2015a), the flexural strength of LWSCC with three different types of LWA were found to be 9.8%-10.5% of the compressive strength. LWSCC with furnace slag as aggregates was able to achieve the highest flexural strength among the three types of aggregates while LWSCC with expanded clay as aggregates achieved the lowest. The authors mentioned that quality, size, and volume of coarse aggregate would affect the flexural strength of LWSCC. The authors developed the mathematical correlation expression of LWSCC flexural strength to compressive strength which is quite similar to normal SCC. This is shown as Equation 1.

$$f_f = 0.1702f_c^{0.8482} \quad \text{Equation 1}$$

Grabois et al. (2016) stated the incorporation of steel fibers in LWSCC did not significantly improve the flexural strength. In short, there is limited research for flexural strength of LWSCC since it is not the main interest of the research and its application is not well established.

5.3 Tensile strength

Concrete is generally weak under tension action. The tensile strength of concrete is commonly used to estimate the load that will cause the development of cracking in the member under flexural loading. Once the concrete cracks, the concrete behaviour will be affected (Malárics & Müller, 2010). In the research done by Corinaldesi and Moriconi (2015), the LWSCC tensile strength did not improve with the addition of synthetic fibers. By referring to the works done by Lotfy et al. (2015a), similar trends were found in tensile splitting strength with compressive strength. LWSCC with expanded shale as LWA achieved the highest strength and expanded clay attained the lowest. The authors developed the mathematical correlation expression of

LWSCC tensile splitting strength to compressive strength. This is shown as Equation 2. They compared the accuracy of their equation for estimating tensile splitting strength from compressive strength with equations from fib model code and ACI 318. They noticed that the fib code equation extremely underestimated the tensile splitting strength of lightweight concrete.

$$f_t = 0.0177f_c^{1.33} \quad \text{Equation 2}$$

The study conducted by Grabois et al. (2016), the tensile strength of LWSCC was determined under direct tensile loading. Tensile strength of LWSCC was found to be improved for about 30% with the addition of steel fibers. They stated that addition of small amount of steel fibers in LWSCC could improve the tensile strength up to the first crack under direct tensile loading. Nevertheless, more study concerning the tensile strength of LWSCC is essential for it to fully replace conventional concrete in any structure.

5.4 Modulus of elasticity

The modulus of elasticity (E -value) is defined as the ratio between normal stress to strain below the proportional limit of a material. It is used to measure instantaneous elastic deformation which represents the stiffness of materials. According to Neville (2008), the E-value of concrete decreased with the use of LWA. The stiffness of LWA is generally very weak which is proven by a few researchers (Floyd et al., 2015; Grabois et al., 2016; Lotfy et al., 2015a). Limited research has been done on the elastic modulus of LWSCC. In the studies of Grabois et al. (2016), the Young's modulus of their LWSCC showed linear elastic behaviour of up to 60% of total stress. The authors explained that the use of expanded clay LWA could improve the bonding between mortar and aggregates which resulted in delay of microcracking process. Also, the authors observed that the addition of steel fibers would decrease the Young's modulus of LWSCC, which was similar to the compressive strength. Floyd et al. (2015) compared the experimental Young's modulus to the calculated values by using ACI equations. The difference

between experimental and calculated values was within 10% and Young's modulus was over-predicted by ACI equation for high strength LWSCC. The Young's modulus showed similar values for LWSCC made of expanded clay and expanded shale which indicated that these two types of aggregates having similar stiffness. In brief, the use of LWA in SCC leads to lower value of elastic modulus. This may be due to the weakness of the porous nature of common LWA.

5.5 Remark

In contrary to normal SCC, the compressive strength of LWSCC is mainly governed by the homogeneity of the batched concrete. The uniformity and homogeneity of LWSCC are governed by the mixing time and procedure. As highlighted by Li et al. (2017), mixing time should not be longer than 3 minutes in order to avoid segregation. Longer mixing time can cause LWA to segregate and float at the top part of specimen. Consequently, the hardened specimen has unbalanced aggregates distribution with more aggregates at top part and more cement mortar at the bottom part which can result in poor compressive strength. Well distribution of aggregates throughout the matrix of concrete can maximize its compressive strength. It can be said that the strength variability of LWSCC can be related to its aggregates distribution and hence is the function of segregation resistance.

Since the mortar of LWSCC is normally stronger than LWA, the compressive strength of LWSCC is also dependent on the strength and proportion of LWA. The compressive strength of LWSCC is sensitive to changes in mix component properties and their proportions such as water to binder ratio, binder content and the incorporation of supplementary cementitious materials. These factors must be considered properly in mix design in order to achieve anticipated workability in fresh state and compressive strength in hardened state. The optimum implementation of supplementary materials such as fly ash, slag and silica fume can improve

compressive strength. In addition, the incorporation of fibres such as steel, synthetic and macro fibers will increase compressive strength of LWSCC.

6.0 Prospective and Future challenges

The recent and present research works provide framework for further investigation and study for utilization of lightweight aggregates in self-compacting concrete. Future research should concentrate on the investigations of the followings.

1. The current methods for developing mix design of lightweight self-compacting concrete are complicated and require the validation through trial laboratory work. Further research is required to develop easy and simple guidelines for developing mix design of lightweight self-compacting concrete. One recommendation is to carry out statistical analysis of the relationship between mix design and performance in terms of fresh and hardened properties.
2. Most of the current research done on LWSCC is restricted to a few types of lightweight aggregates only. Furthermore, there is limited research on the use of other types of lightweight aggregates such as sintered slate, sintered pulverized fuel ash, oil palm shell, colliery waste, etc in LWSCC as they have been used as LWA in lightweight concrete (LWC). Effort must be made to identify more variety of suitable aggregates.
3. There is limited research on the long term durability behaviour of LWSCC such as shrinkage, creep, corrosion and bond strength. Moreover, these properties are not considered in the mix design methodology. Further research is required in this area.
4. More study is recommended to understand the tensile strength, flexural strength, elastic modulus, shear characteristic, and pre-stressing application of LWSCC.
5. The use of LWSCC technology at the present moment is restricted to research only. It will be a big challenge to further develop and refine this technology to be adopted and widely used in construction industry.

7.0 Conclusions

The application of lightweight aggregates in lightweight self-compacting concrete is reviewed based on recent literatures and the outcome is reported in this paper. The physical properties of LWA, mix design methodology, fresh and hardened properties of LWSCC were discussed. From the literature review, the following conclusion can be made.

1. Different LWA exhibit different specific gravity, size gradation, shape characteristic, bulk density and water absorbability which lead to different performance of LWSCC. LWA of specific gravity less than 2.0 is commonly utilized to manufacture LWSCC. The maximum LWA sizes are limited to the range of 12.5 to 16mm. The shape of LWA commonly varies from spherical to flaky. Different LWA exhibit different water absorption which varies from 5%-80%. In this regards, saturated surface dry condition has to be achieved to reduce water sensitivity.
2. The workability of LWSCC depends on the aggregates packing density and void volume. Water to binder ratio, superplasticizer dosage and total binder content have great bearing on the performance of LWSCC workability. The inclusion of different types of supplementary materials has different effects on LWSCC workability. The use of silica fume as well as with its increasing replacement level, improve the segregation resistance of LWSCC but have negative effect on filling and passing ability. The inclusion of fly ash as binary or ternary blend will not only improve all the three fresh properties but also reduce the amount of SP required.
3. The compressive strength of LWSCC is highly dependent on the strength of LWA as they are weaker than the mortar. Factors such as water to binder ratio, binder content and the incorporation of supplementary cementitious materials will affect the compressive strength of LWSCC significantly and they must be considered properly in mix design. Optimum inclusion of supplementary materials such as fly ash, slag and silica fume will improve the

compressive strength. Also, fibres such as steel, synthetic and macro fibers will increase the compressive strength of LWSCC

4. This review enhances the understanding of LWSCC mix design methodology with close aggregate packing method being most commonly practiced. Close aggregate packing method establishes the relationship between paste and aggregates. Some researchers have introduced statistical analysis to simplify and improve the design procedures. Close aggregate packing principle provides clear insight into the understanding of consumption of aggregate and paste volume for a given unit volume of concrete.

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