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Research Article

Engineering Properties and Sustainability Assessment of Recycled Glass Sand Concrete

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Abstract

Reduction in the availability of natural raw materials is forcing concrete industry to adopt environmentally friendly approaches. Utilization of recycled materials in concrete production has become a popular approach to lessen the environmental footprint of the concrete production. Glass is one of the most consumed materials that can be easily collected and recycled. Glass use in concrete production may potentially reduce the amount of natural raw materials used in concrete production and prevents the use of virgin lands for landfilling purposes. Reported work initially investigates the fresh and hardened performances of recycled glass sand (RGS) incorporated concrete and further sustainability analysis was also carried out. As an initial attempt for this particular research, natural sand was replaced by 10% RGS in aiming to assess their suitability from the environmental and economical sustainability point of view. In this regard, concretes made with partially substituted RGS (10% by mass replacement) with equivalent 28-day compressive cube strengths of 30 N/mm^2 and 45 N/mm^2 were produced.

The results showed that the use RGS could improve concrete fresh properties slightly. Use of RGS by 10% as a replacement to natural fine aggregate was observed to reduce compressive strength at early ages by approximately 10% and 14% but strength losses were minimized to 0.6% and 10.5% for 30-RGS and 45-RGS respectively at 28-days compared to conventional concrete mixes. Ultrasonic pulse velocity results showed that RGS incorporation provide either similar or denser matrix compared to conventional mixes. Results indicated that use of RGS as a fine aggregate replacement could lead to environmentally sustainable concrete production if it is supplied within range of 14.4 km based on eCO_2 emissions. It is also revealed that RGS could provide cost-efficient concrete production on the condition of supplied from closer facilities.

Keywords: Recycled glass sand, Sustainability, Ultimate compressive strength, Ultrasonic pulse velocity

Geri Dönüştürülmüş Cam Kumlu Betonun Mühendislik Özellikleri ve Sürdürülebilirlik Değerlendirmesi

Öz

Doğal hammadde mevcudiyetindeki azalma, beton endüstrisini çevre dostu yaklaşımlar benimsemeye zorlamaktadır. Beton üretiminde geri dönüştürülmüş malzemelerin kullanılması, beton üretiminin çevresel ayak izini azaltmak için popüler bir yaklaşım haline gelmiştir. Cam, kolayca toplanıp geri dönüştürülebilen en çok tüketilen malzemelerden biridir. Beton üretiminde cam kullanımı, beton üretiminde kullanılan doğal hammadde miktarını potansiyel olarak azaltabilir ve atık gömme icin kullanılan bakir arazilerin depolama amacıyla kullanılmasını önler. Rapor edilen çalışma başlangıçta geri dönüştürülmüş cam kumu kullanılarak üretilen betonun taze ve sertleşmiş performansını araştırmış ve daha sonra da çevresel ve ekonomik sürdürülebilirlik açısından uygunluklarını değerlendirmek için sürdürülebilirlik analizi de yapılmıştır. Bu bağlamda, 30 N/mm^2 ve 45 N/mm^2 eşdeğer 28 günlük basınç dayanımına sahip kısmen cam kumu ikame (ağırlıkça %10) edilerek yapılan betonlar üretilmiştir.

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Sonuçlar, geri dönüştürülmüş cam kumu kullanmanın, betonun taze özelliklerini bir miktar iyileştirebileceğini göstermiştir. Geri dönüştürülmüş cam kumunun doğal ince agreganın yerine %10 oranında kullanılmasının, erken yaşlarda basınç dayanımını yaklaşık %10 ve %14 oranında azalttığı gözlenmiştir, ancak basınç kayıplarının 30-RGS ve 45-RGS için normal beton karışımlarına kıyasla sırasıyla 28 günde % 0.6 ve% 10.5'e düştüğü gözlemlenmiştir. Ultrases geçis hızı sonuçları, geri dönüştürülmüş cam kumu kullanımının, normal karışımlara kıyasla benzer veya daha yoğun matris sağladığını gösterdi. Sonuçlar, geri dönüştürülmüş cam kumunun iyi bir agrega değişimi olarak kullanılmasının, 14,4 km'lik bir alanda tedarik edilmesi halinde çevresel olarak sürdürülebilir beton üretimine katkı sağlayabileceğini göstermiştir. Ayrıca geri dönüştürülmüş cam kumu, daha yakın tesislerden tedarik edilmek koşuluyla uygun maliyetli beton üretimi sağlayabildiği de ortaya çıkmıştır.

Anahtar Kelimeler: Geri dönüşümlü cam kumu, Sürdürülebilirlik, Basınç dayanımı, Ultrases geçiş hızı

1. Introduction

Concrete is the second most consumed material in the world after water (Gagg, 2014). It is estimated that approximately 4.4 billion tonnes of concrete is being produced annually for different applications (Hilburg, 2019). Even though concrete is known to be more environmentally friendly amongst construction materials, its contribution to global CO_2 is ranged between 4-8% (Watts, 2019). Portland cement (PC) is responsible for approximately 90% of these emissions and aggregates are treated as low carbon constituent in concrete production (Mineral Products Association, 2019). In addition, aggregate characteristic is one of the key factors in determining the rigidity, stiffness and volumetric stability (Alexander and Mindness, 2010). Using high volumes of natural aggregates in concrete production has significant negative impact on the environment as availability of high quality natural sand is running low (Hajimohammadi, 2018). A market research reported 47 billion tonnes of aggregates were used in the construction industry in 2018 and it is expected to reach 63 billion tonnes by 2024 (Persistence Market Research, 2019). Sustainable development requires preservation of natural resources. Waste product use in concrete production is a globally well accepted approach to encourage sustainability in concrete industry. In addition to this, developing countries started to increase the pressure on concrete suppliers by increasing the taxes on natural material extraction in order to encourage the use of recycled materials use in concrete production. This fact could also lead to production of economically friendly concrete production when waste materials are utilized. In order to be environmentally friendly approach, concrete constituents should be locally available due to collection and transportation of these material could contribute to embodied CO_2 emissions and cost of final product which could result in an unsustainable concrete production. Several waste materials have been utilized in either cement paste or concrete to minimize the environmental destruction through concrete production (Aydin, 2019; Bilir, 2015; Demirel, 2019; Gesoglu, 2017; Uçal, 2018; Ulubeyli, 2017).

The effects of the recycled or waste glass on the concrete fresh and hardened properties are not yet clear. According to Limbachiya (Limbachiya, 2009), fresh properties of concrete could be negatively affected when natural fine aggregates were replaced by 30% recycled glass sand (RGS). Rashid (Rashid, 2018) reported reduction in slump as the glass waste content increased. Adaway (Adaway, 2015) found that 15% glass replacement level as fine aggregate increased the slump slightly. A study by Soliman (Soliman, 2017) reported improvements in fresh properties with higher RGS replacement levels. In addition to these, Sadiqul Islam (Sadiqul Islam, 2017) reported a gradual increase in fresh properties when PC is replaced by glass powder up to 25% replacement levels. In contrast to that, Bourgiba (Bourgiba, 2017) reported decreased workability when recycled sand is introduced due to higher porosity of the recycled sand. In addition, a study by Tan (Tan, 2013) showed that similar fresh properties as conventional mix can be achieved when 25% green RGS is used. Same study also reported reduction in fresh properties when RGS is increased due to having sharp edges and angular shape which required more water to coat the mix. However, Ling (Ling, 2011) claimed that recycled glass (RG) mixes improved fresh properties due to the fact that RG was coarser than natural sand led to lower water absorption and thereby lower water demand.

A study by Tan (Tan, 2013) revealed reduction in fresh density as the RGS content increased. Similar finding was also noted by Ismail (Ismail, 2009). From the hardened properties point of view, Rashid (Rashid, 2018) reported slight reductions for the bulk density as the glass waste content is increased. 2% reduction was observed when 30% of glass waste was used. Hajimohammadi (Hajimohammadi, 2018) found similar density between conventional and glass utilized samples. Another study by Guo (Guo, 2018) revealed that use of glass aggregates with 100% replacement level led to reduction in hardened density due to lower specific gravity of glass compared to natural sand. Up to 3% of reduction in unit weight was noted by Soliman (Soliman, 2017) when natural sand was fully replaced by RGS. Penacho (Penacho, 2014) explained the reduction of glass utilized mortars which could be due to angular shaped of RGS led to reduction in the bulk density of RGS compared to natural sand.

As far as the ultimate compressive strength (UCS) is concerned, Sadiqul Islam (Sadiqul Islam, 2017) reported that use of RG powder as a PC replacement which is finer than 100 µm size increase pozzolanic reactivity of glass and could improve mechanical and durability performances of glass incorporated concrete. Pozzolanic contribution of glass either as a sand (Arulrajah, 2017; Bostanci, 2018; Corinaldesi, 2016; Guo, 2018; Hajimohammadi, 2018; Harbi, 2017; Idir, 2011; Ling, 2011; Nunes, 2013; Paul, 2018; Penacho, 2014; Rashid, 2018; Soliman, 2017) or cement (Carsana, 2014; Du, 2017; Paul, 2018) replacements was reported earlier. Özkan (Özkan, 2008) also reported that the effect of glass on the strength development increased when it is finely ground. Limbachiya (Limbachiya, 2009) reported that similar strengths could be achieved with 20% replacement levels of RGS. However, a study by Özkan (Özkan , 2008) reported that either similar or higher UCS values can be achieved at 7 and 28 days with 10% RGS replacement levels. Siad (Siad, 2018) stated that RG powder with average grain size of 20 µm acted as a catalyst rather than pozzolanic property and contributed to early strength development. Another study by Rashid (Rashid, 2018) observed that use of waste glass with nominal aggregate size of 20 mm reduced the UCS at 7 and 28 days as the glass waste increased. However, strength loss of 10% waste glass mix was observed to be negligible. Afshinnia (Afshinnia, 2016) reported that decrease in UCS which is believed to be due to weaker bond between the cement and aggregate pastes. A review study by Paul (Paul, 2018) stated that 20% of RG used either as aggregate or cement replacement did not have any significant effect on the UCS. Harbi (Harbi, 2017) stated that reduction in UCS could be linked with the lower density of the glass and thus not able to fill the pores. A study by Hajimohammadi (Hajimohammadi 2018, Hajimohammadi 2018) revealed that using 30% glass fines with dimensions between 0.4 to 2 mm contributed to early strength development at 7 days. However, same mix resulted in lower strength development between 7 and 14 days but higher strength development between 28 and 56 days. In addition, Penacho (Penacho, 2014) found that RGS replacement up to 50% improves the UCS. Guo (Guo, 2018) used 100% glass replacement to natural sand with glass aggregates being finer than natural sand and found significant reductions in strength development up to 28 days. Similar trend was also observed for Soliman (Soliman , 2017) that 100% replacement level by RGS led to reduction in UCS considerably due to rough and elongated nature of RGS.

From the economical point of view, Siad (Siad, 2017) stated that use of RGS could provide cost efficient concrete. Soliman (Soliman, 2017) reported 4% and 11% reductions, exclusing the transportation of materials, in cost for both 50% and 100% RGS replacement levels respectively. Soliman also reported that further reductions can be achieved if locally available materials are used.

There is no specific agreement on the use of RGS and its effect on both fresh and hardened properties. In addition, there are few data on the feasibility of using RGS in concrete production as a replacement to fine aggregates from the environmental and economical sustainability point of view. In the light of these, this particular research focusses on two different strength class concrete mixes made with 10% partially replaced RGS as a replacement to natural fine aggregates. Environmental and economical sustainability analyses were also carried out to identify under which conditions RGS use in concrete could be an environmentally friendly and economically viable approach on the course of sustainable development.

2. Experimental Programme

The research programme was carried out considering fresh and mechanical performances, environmental assessment and finally practical implications.

2.1. Materials

Portland cement was used for the production of control mixes in conformity with TS EN 197-1 (Turkish Standards Institution, 2012). The Blaine fineness of the PC was 305 m^2/kg and its specific gravity was 3.15. Natural aggregates were obtained from the local suppliers. A single brand recycled bottles was collected and RGS was obtained through this domestic waste. Then, glass bottles were broken and sieved through 5.6 mm sieve sized. Prior to mixing, RGS was washed and left to surface dry then RGS was used in concrete production in a saturated surface dry state. Natural sand and gravel used were having nominal sizes of 5.6 mm and 22.4 mm respectively in conformity with TS 706 EN 12620+A1 (Turkish Standards Institution, 2009). Physical and mechanical properties of the aggregates used are given in Table 1. Grading of aggregate types used is given in Figure 1. MasterGlenium 126, a Polycarboxylic ether based versatile superplasticizer, was used as an admixture in conformity with TS EN 934-2.

Table 1. Physical and mechanical properties of aggregates used

Physical Properties *(TS EN 1097, part 6)*	Type of aggregates		
	Gravel	Sand	
		Natural	Recycled
Unit weight (kg/m^3)	1.65	1.52	1.50
Apparent density (kg/m^3)	2.76	2.71	2.61
Water absorption capacity (%)	1.13	0.12	1.40
Specific gravity	2.74	2.69	2.59

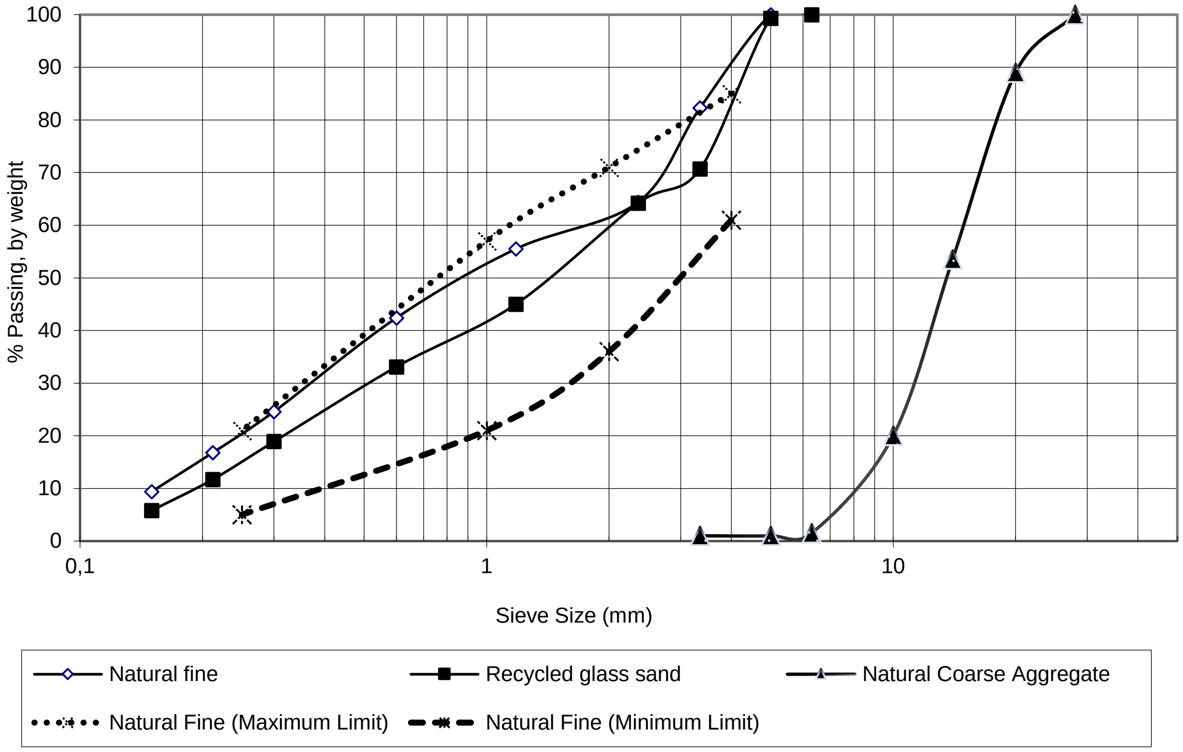

Figure 1. Particle size distribution of natural and recycled aggregates used in this study

2.2. Mix Proportions and Concrete Mix Design

Quantities of constituents were determined through using Building Research Establishment mix design method. Following this, trial mixes were carried out to achieve 28-day cube design strength of 30 and 45N/mm^2. Mix designs were based on the relative density of the natural gravel. Concrete densities were kept constant as 2325 kg/m^3 for all mixes. Mixes were aimed to have workability class of S2 class in accordance with TS EN 206:2013+A1 then water/cement (w/c) ratios were computed as 0.45 and 0.64 for 30 and 45 N/mm^2 28-day cube design strength concretes respectively. Total cement and aggregate contents were kept the same for both concrete grades. First mixes cast were made with PC and natural gravel and sand aggregates. Then, second mixes were made with PC, natural gravel and sand but natural sand was replaced by RGS with replacement level of 10% on mass basis. Based on target workability, admixture contents were kept as 0.5% of PC content for all mixes. Mixes were denoted as 30-NA and 45-NA whilst RGS utilized mixes were denoted as 30-RGS and 45-RGS 30 and 45N/mm^2 28-day cube design strength concretes respectively. Mix proportions established for both strength class concrete mixes are provided in Table 2.

Table 2. Mix design of concrete mixes

Strength class	Mixes	Mix Proportions (kg/m^3)					
		Water	PC	Aggregates			Admixture
				Sand		Gavel	
				Natural	RGS		
C30	NA	215	335	965	-	810	1.68
	RGS	215	335	870	95	810	1.68
C45	NA	220	490	825	-	790	2.45
	RGS	220	490	740	85	790	2.45

2.3. Test Procedures

Concrete production and testing were carried out in conformity with TS EN 12350:2010 Parts 1(TSE, and 2. Following this, slump test for each mix was carried out. Cast mixes were then weighted for the fresh density determination. Concrete mixes were then covered with polythene sheets for 24 hours to maintain moist condition. Mixes were demoulded and water cured until the testing age in conformity with TS EN 12390-2:2010. Hardened properties investigated were UCS, Schmidt Hammer and Ultrasonic Pulse Velocity (UPV). UCS development of developed mixes was determined at 1, 7, 14 and 28 days through 150 mm cube samples in accordance with TS EN 12390-3:2010. Schmidt Hammer and UPV tests were performed at 28 days. Prior to UCS test, same samples were used for non-destructive Schmidt Hammer testing. 150 mm cubes were also used for the determination of UPV test results.

2.4. Sustainability Assesment

Sustainability performances including environmental, economical and social aspects were also evaluated for the developed mixes. Environmental and economical sustainability assessments were carried out considering European University of Lefke as the production site and transportation distance were taken into account accordingly. Environmental sustainability covered the eCO_2 emissions calculations which are based on the information provided by the relevant stakeholders and the available data.

The eCO_2 emissions were obtained depending upon the quantity and the value that is obtained for each material. In addition, eCO_2 emissions were also calculated based on the distance from the place of collection and casting site, European University of Lefke. For concrete constituents PC is imported from Turkey. This requires PC to be transported to port from the extraction and then through seaway to North Cyprus. This is followed by transportation from port to silo, storing in silo and then transporting to the casting site. Emission based on PC use is worked out in collaboration with Kascon Readymix Concrete Company. In addition, eCO_2 emissions for the extraction of natural aggregates were calculated based on the existing literature and also in collaboration with the local supplier Üstaş Ltd. Table 3 gives the equivalent eCO_2 emissions of constituents used based on the embodied energy generated for the extraction and production of each constituent.

The eCO_2 emission value of RGS for production is used as 0.164 kg CO_2 per batch due to energy use during crushing process of RGS. This value was calculated based on the national energy tariff, energy consumption of test equipment and duration of crushing. Total eCO_2 emission for transportation is used as 9.33 kg CO_2 regardless of the quantity of RGS used. This value was calculated based on the CO_2 emissions of light duty vehicle and transportation distance from the collection point to production site (European Parliamentary Research Service, 2018).

Cost analysis also based on the relevant information provided by the relevant stakeholders and up-to-date petrol tariffs regarding to transportation costs. Cost of materials and their transportation distances are given in Table 4. Cost calculations were also carried out following the same approach as the eCO_2 emission calculations. Based on the environmental and economical assessments, suggestions were provided to state under which circumstances these materials can be environmentally and economically efficient approaches. Social aspect is also investigated based on the growing social concern on the quarrying of natural raw materials.

Table 3. eCO_2 emissions for the production of materials used

Process	Materials	eCO_2 emission (kg CO_2/kg)
Production	Aggregates	*0.005(1)
	Portland cement	*0.710(1)
	Water	*0.000155
	Admixture	*0.0022
Transportation	Aggregates	*0.32
	Portland cement (through mainland transportation)	*0.32(2&3)
	Portland cement (through seaway transportation)	*0.007(2&3)
	Admixture	*0.138

(1) Bath Inventory; (2) International Maritime Organization; (3)Rossit, G. & Lawson, M.; * represents data obtained from the suppliers and available scientific sources. *Water eCO_2 emissions were obtained from North Cyprus relevant governmental body; Aggregates eCO_2 emissions through transportation were calculated depending on the distance from the extraction to production site in collaboration with KASCON Ready-mixed concrete company.

Table 4. National transportation distances and costs of materials

Materials	Transportation distance (km)	Cost ($/tonne)	
		Production	Transportation
Natural aggregates	72.5	4.46	3.21
RGS	57.3	0.064	8.01
PC	116.5	75	3.57
Admixture	64.4	625	9

3. Results and Discussion

3.1. Fresh Properties

3.1.1. Slump Test

Slump value of developed mixes are given in Figure 2. It is clear from the results that RGS incorporation resulted in a slight increase for strength classes. This supports previous findings (Adaway, 2015; Sadiqul, 2017; Soliman, 2017). This is believed to be due to presence of chemical admixture resulted in better dispersion of RGS and mitigated the negative effect through irregular grain shape of RGS. In addition, chemical admixture also believed even though RGS had higher water absorption than natural fine aggregate. The results are also in line with Ling (Ling, 2011) that coarser characteristics of RGS, as can be seen from Figure 1, compared to natural fine aggregate might have reduced water absorption and required lower water demand.

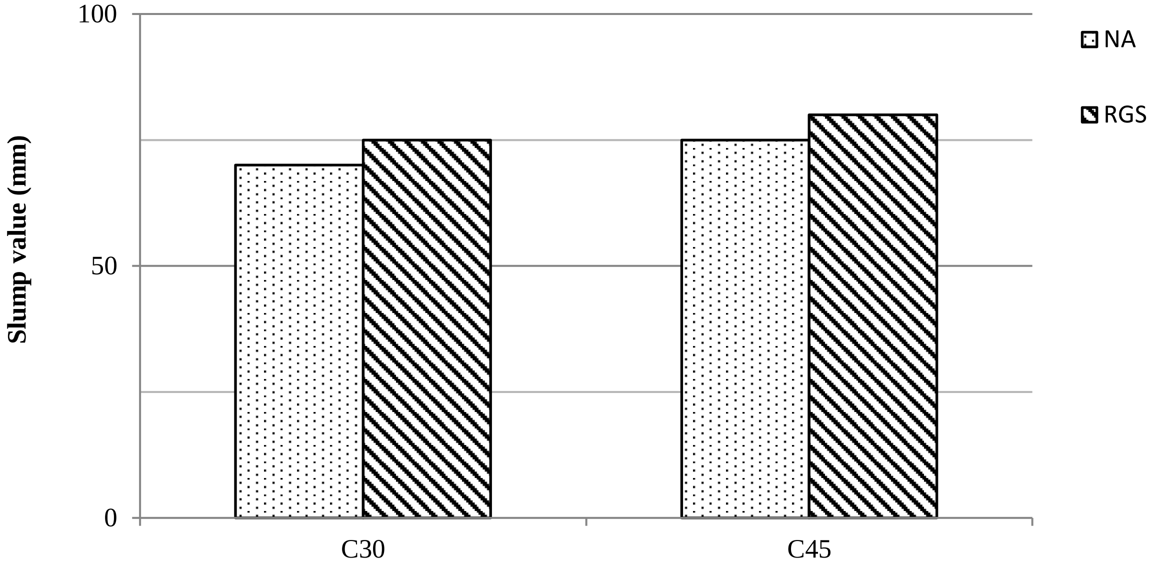

Figure 2. Slump test results

3.1.2. Fresh Density

Fresh density results of concrete mixes are given in Table 5. There is no specific trend observed from the results. RGS use as a replacement to fine aggregate was observed to increase fresh density for both strength classes. The results are in agreement with previous researches by Tan (Tan, 2013) and Ismail (Ismail, 2009). In addition, sharp increase of 30-RGS mix may be explained due to environmental factors, temperature in particular and humidity, might have contributed to the increase in the density.

Table 5. Fresh Density Results

Concrete Strength Class	Mix	Fresh Density (kg/m^3)
C30	NA	2264
	RGS	2390
C45	NA	2240
	RGS	2276

3.2. Hardened Properties

3.2.1. Hardened Density

Hardened density values are revealed in Table 6. The results showed contradictory trends observed for both strength classes. Both mixes had quite similar results. RGS incorporation resulted in 1% reduction for C30 strength class concrete whilst indicated 1% increase for C45 strength class concrete. The reduction observed for 30-RGS mix is in line with previous researches (Guo, 2018; Rashid, 2018; Soliman, 2017). The contradicting results between two strength classes could be explained by due to 30-RGS mix content had more fine content which may lead to increased water absorption and resulted in decrease in hardened density. In addition, this may also due to angular shaped RGS particles may result in the reduction in hardened density (Penacho, 2014). Contradictory result for 45-RGS mix may be due to lower RGS content and higher cement contents reduced the total angular material presence and provided better dispersion amongst for that particular mix. This, then, eliminated the negative effect of angularity reported by 30-RGS mix and increased hardened density compared to conventional 45-NA mix.

Table 6. Hardened Density Results

Concrete Strength Class	Mix	Fresh Density (kg/m^3)
C30	NA	2254
	RGS	2227
C45	NA	2237
	RGS	2260

3.2.2. Ultimate Compressive Strength

UCS results are given Figure 3 and Figure 4 for C30 and C45 concrete strength class concretes respectively. Results showed that RGS use reduced the early UCS of both strength class mixes. Similar findings were reported earlier (Afshinnia, 2016; Rashid, 2018; Soliman, 2017). Strength losses at 1 day were recorded as 30% and 29% for C30 and C45 concrete strength classes respectively. This is in line with Hajimohammadi (Hajimohammadi, 2018) that RGS with finer characteristics (between 0.4-2 mm) may contribute to strength development at early ages. As RGS used had nominal size 5.6 mm, this may diminish the contribution of RGS to early strength development. This reduction can be attributed to irregular shape of RGS compared to natural fine aggregate may lead to weaker bonding between cement and aggregate pastes (Afshinnia, 2018). This strength can also be attributed to rough and elongated nature of RGS compared to natural fine aggregate led to reduction in compressive cube strength (Soliman, 2017). However, these loses were lessen at 7 days having reported 6% and 22% strength losses for 30-RGS and 45-RGS concrete mixes respectively in comparison to NA mixes. The improvement also agree with the suggestion reported by the author earlier on hardened density regarding to having more finer content for 30-RGS concrete mix may have filled the finer pores and resulted in only 6% strength loss compared to conventional 30-NA concrete mix. For C30 strength class mixes, RGS incorporation decreased UCS by 1% at both 14 and 28 days whilst 10% strength loss at both days 14 and 28 days were observed for C45 strength class mix compared to conventional control mixes. This improvement supports the fact by previous research reported earlier (Limbachiya, 2009) that RGS content up to 20% does not have negative effect on concrete UCS at 28 days. Also, the improvement in UCS from very early age until 28 days is believed to be due to Silica presence in RGS may have contributed to the formation of Calcium-Silica-Hydrate gel.

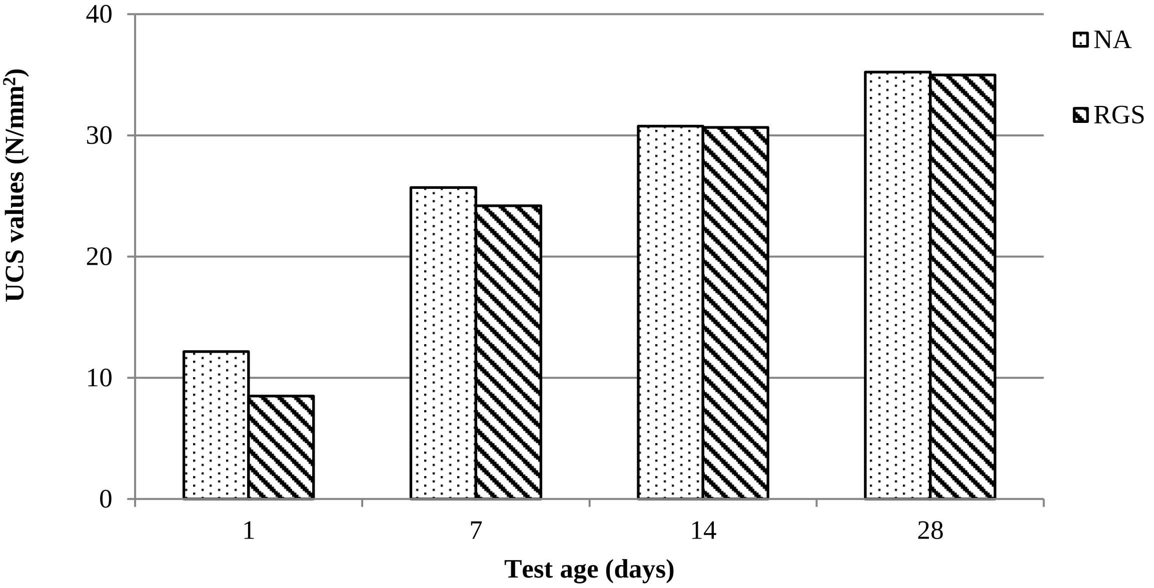

Figure 3. UCS results for 30 N/mm^2 28-day design strength concrete mixes

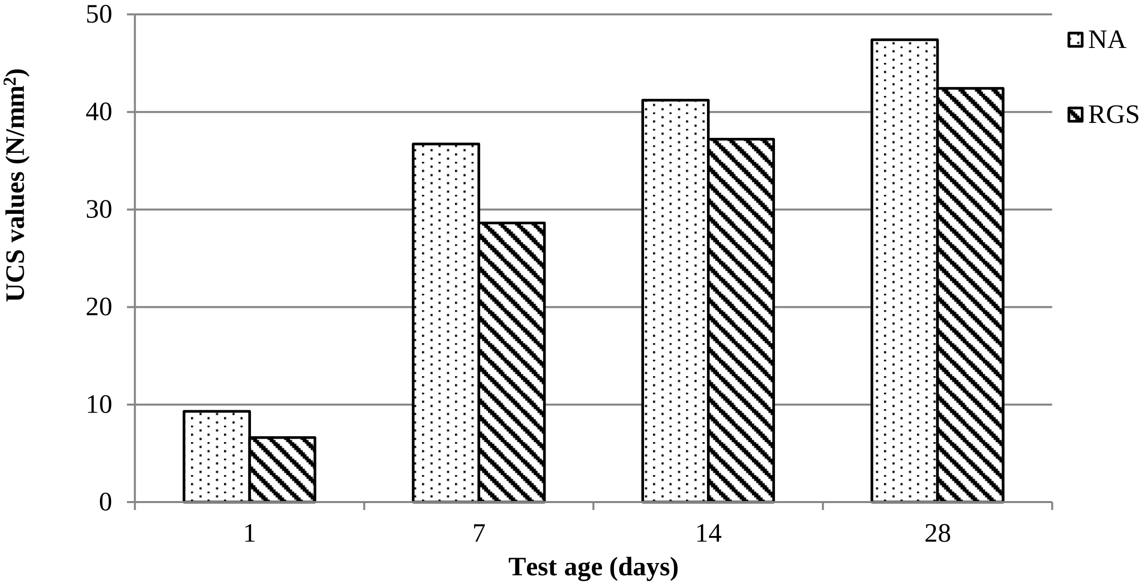

Figure 4. UCS results for 45 N/mm^2 28-day design strength concrete mixes

3.2.3. Schmidt Hammer

Schmidt Hammer test results are revealed in Table 7. Non-destructive test methods have gained popularity for the determination of uniformity and indication of UCS of the existing concrete structures. Quite similar trend as UCS was reported. 30-RGS mix was observed to achieve higher rebound number compared to 30-NA mix whilst 45-RGS mix reported lower rebound number compared to 45-NA mix. Schmidt hammer test results also support facts stated earlier for UCS (Afshinnia, 2018; Limbachiya, 2009). Ratios between Schmidt Hammer and UCS results were reported as 0.49 and 0.50 for 30-NA and 30-RGS mixes respectively. In addition, 45-NA and 45-RGS mixes reported ratios of 0.44 and 0.45 respectively.

Table 7. Schmidt Hammer test results

Concrete Strength Class	Mix	Rebound Number (N/mm^2)
C30	NA	17.1
	RGS	17.5
C45	NA	20.7
	RGS	18.9

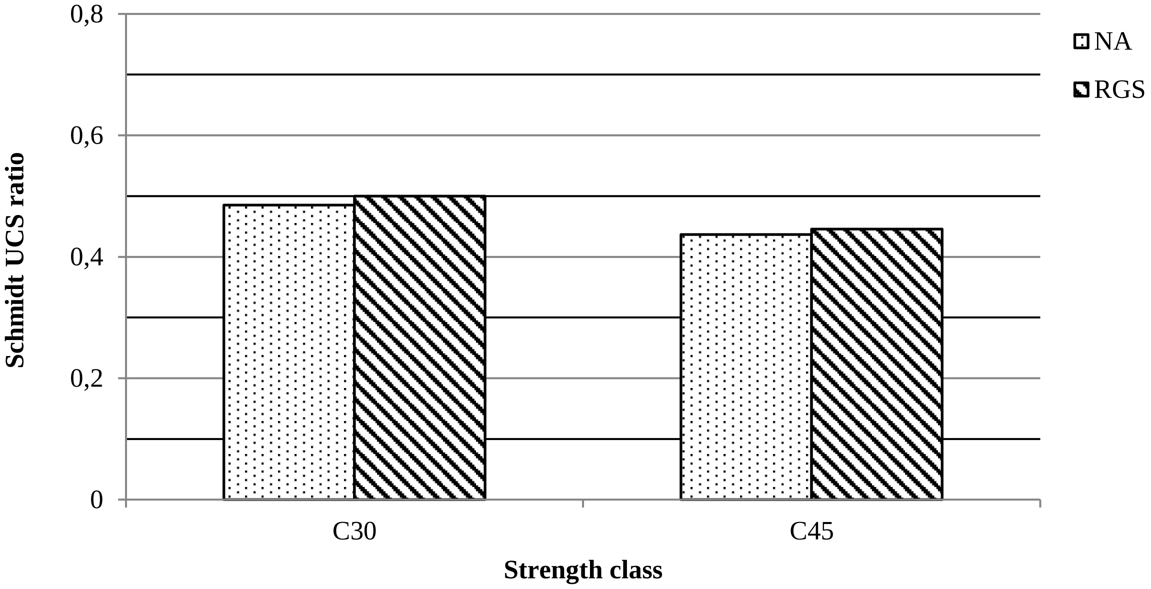

Figure 5. Relationship between Schmidt Hammer and UCS results

3.2.4. Ultrasonic Pulse Velocity

UPV test results are provided in Table 8. There is no specific trend observed from the results. However, results are quite in line with UCS results. UPV values were observed to increase as the concrete strength class increases due to increase in the finer material content for C45 strength class mixes. 30-RGS was observed to increase UPV whilst 45-RGS reported slightly lower UPV value compared to control mixes. Higher UPV value of C30 strength class concrete could be explained by surface and texture of RGS, even though rougher and angular, may have provided better particle packing amongst constituents. This can be also seen through UCS results of 30-RGS mix.

Table 8. Ultrasonic Pulse Velocity

Concrete Strength Class	Mix	UPV (m/s)
C30	NA	4094
	RGS	4465
C45	NA	4834
	RGS	4727

3.3. Sustainability Performance

3.3.1. Environmental Sustainability

The eCO_2 emissions of developed mixes are revealed in Figure 7. As expected eCO_2 emissions increased as the strength class increased. It can be seen from the results that similar trend for both strength classes were reported. The eCO_2 emissions for NA mixes were noted as 322.1 kg CO_2/m^3 and 433.5 kg CO_2/m^3 for 30-NA and 45-NA mixes respectively. RGS incorporation was observed to increase eCO_2 emissions by 2.11% and 1.64% for 30-RGS and 45-RGS mixes respectively. In fact, aggregates have lower eCO_2 emissions through production and transportation, and replacing them with RGS would increase total eCO_2 emissions due to transportation of RGS to the casting site and resulted in higher emissions. It is also observed from the results that RGS incorporation could be an environmentally sustainable approach on the condition of collecting RGS from the radius of 16.5 km and 14.4 km for 30-RGS and 45-RGS respectively. This is in agreement with the previous statement by the Concrete Centre (Concrete Centre, 2011) and Knoeri (Knoeri, 2013) that recycled aggregate use would be a feasible approach if obtained within 15 km radius. The distribution of eCO_2 emissions through production and transportation is given in Figure 8. Results revealed that eCO_2 emissions through production were calculated as 76.6% and 74.9% for 30-NA and 30-RGS mixes respectively whilst 82.1% and 80.8% for 45-NA and 45-RGS mixes respectively. Even though natural aggregates do not contribute to eCO_2 emissions considerably, replacing natural fine aggregate with RGS and using crusher to achieve required grading (<5.6mm) for RGS would lower eCO_2 emissions through production. The relationship between the eCO_2 emissions and 28-days UCS results is provided in Table 9. It is seen from Table 6 that RGS use resulted in increase in eCO_2 per 1 N/mm^2 by 2.73% and 13.7% for 30 N/mm^2 and 45 N/mm^2 strength classes respectively. Higher increase of 45-RGS mix can be attributed to higher UCS loss compared to 45-NA at 28 days. These increases may be diminished by obtaining RGS from closer distance which will reduce the eCO_2 significantly.

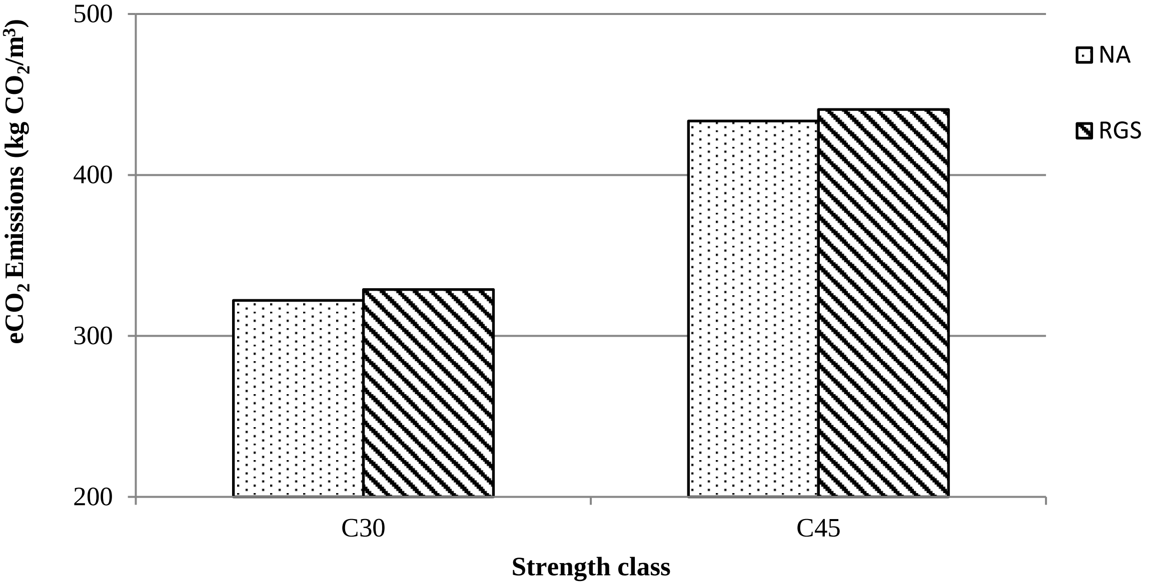

Figure 7. eCO₂ emissions of concrete mixes

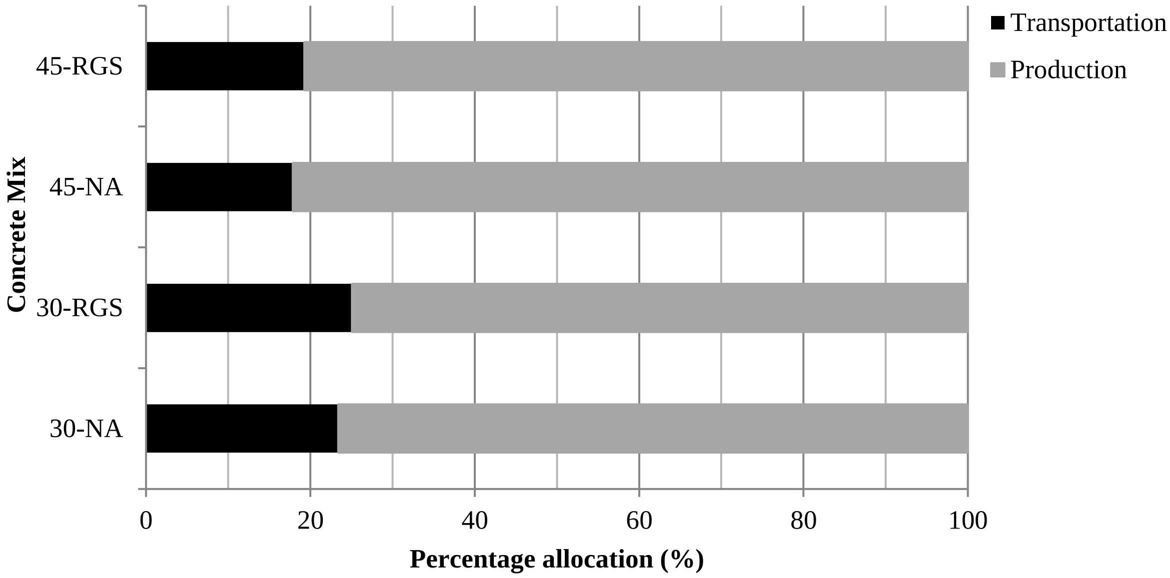

Figure 8. Percentage distribution of eCO₂ emissions of transportation and production of mixes

Table 9. The relationship between environmental and economical sustainability and UCS of concrete mixes

Concrete mix	**eCO₂ emission / 28-day UCS (kg CO₂ / N/mm²)**	**Cost / 28-day UCS ($ / N/mm²)**
30-NA	9.15	1.19
30-RGS	9.40	1.20
45-NA	9.14	1.12
45-RGS	10.39	1.26

3.3.2. Economical Sustainability

Costs of developed concrete mixes are provided in Figure 9. Similar to eCO_2 emission results, cost of concrete mixes was increased as the strength class increased. Results show that RGS incorporation had similar results as concrete mixes. Costs of 30-NA and 45-NA were calculated as $41.82 and $53.26 respectively. RGS use increased eCO_2 emissions by 0.09% and 0.06% respectively which can be negligible. This increase in cost is fully influenced by the transportation of RGS to casting site whereas crushing process is responsible from 0.8% of total cost for both RGS mixes. It can also be concluded from the results that RGS incorporation could be an economically viable approach if obtained from 2.9 km closer facility (54.4 km for this particular research) for both strength classes. The distribution of costs for both production and transportation is given in Figure 10. Cost of production undertakes 83.5% and 85.9% for 30-NA and 45-NA mixes respectively whereas 81% and 85.1% were reported for 30-RGS and 45-RGS mixes respectively. The relationship between cost and 28-days UCS results is provided in Table 9. Results show that RGS use showed increase in cost per 1 N/mm^2 by 0.8% and 12.5% for 30 N/mm^2 and 45 N/mm^2 target design strength concretes respectively. Similar to relationship between eCO_2 emissions and 28-days UCS results, significant increase of 45-RGS mix is due to lower 28-day UCS. As the effect of transportation on cost is higher for RGS mixes than conventional mixes, collecting waste glass from closer facility will also contribute to economical sustainability.

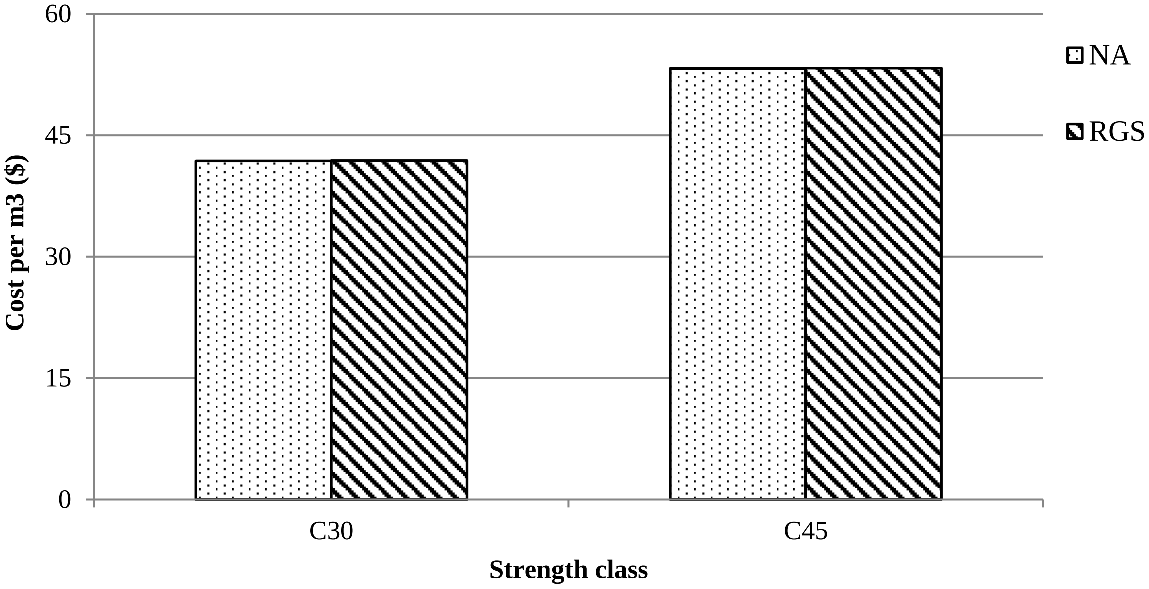

Figure 9. Cost of concrete mixes

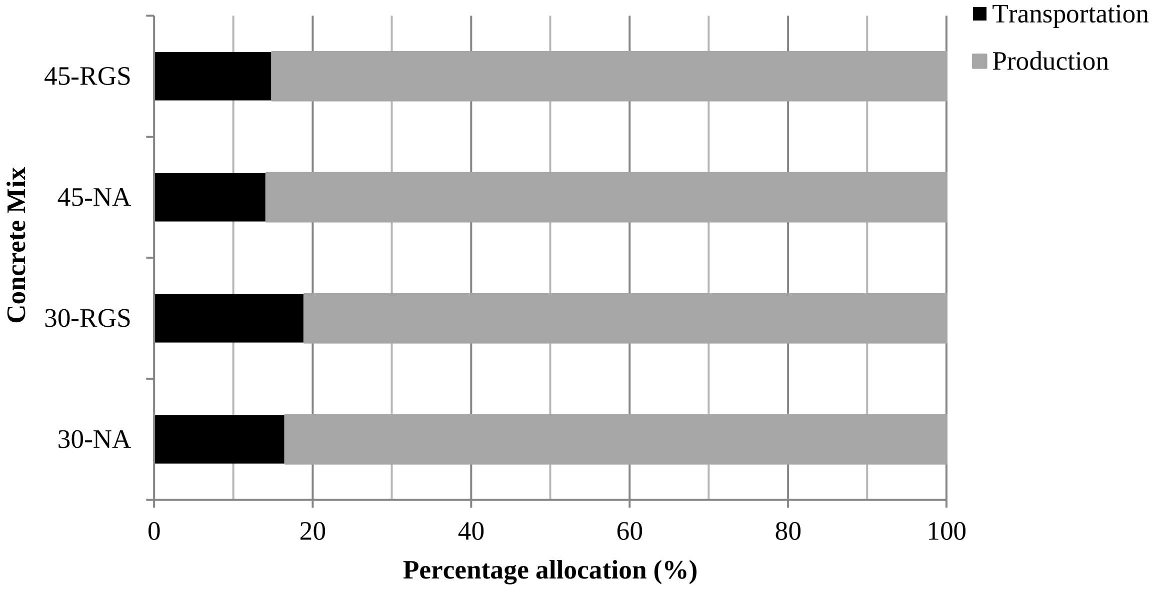

Figure 10. Percentage distribution of cost of transportation and production of mixes

3.3.3. Social Sustainability

Human factor is usually neglected when taking into account the principles of sustainability due to lack of direct numerical contribution. However, sustainability directives and legislations are set up by humankind. There is no strict current legislation in force on the sustainable development in North Cyprus concrete industry. Several environmental organizations have raised the public awareness on the environmental destruction from the quarry sites. In addition, waste materials are usually sent to landfill in North Cyprus due to solid waste storage facility has reached to full capacity. Encouraging concrete industry to utilize waste materials is a necessity in order to provide environmentally friendly concrete production. Glass is one of the most consumed materials in North Cyprus and usually being sent to landfill due to local municipalities does not have necessary recycling and storage facilities. Concrete production is one of most appropriate approach for recycled glass to be benefited and reused. This may contribute to social sustainability through reusing of a waste material and thereby reducing the amount of glass that is sent to landfill and reduce the demand on the quarrying natural raw materials to be used as a concrete constituent.

4. Conclusions and Recommendations

The main conclusions extracted from this research study are as follows;

- Presence of chemical admixture enabled irregular shaped RGS to disperse better in the concrete mix and improved the slump value of mixes slightly.
- RGS incorporation showed sharp reduction for UCS at early ages. Strength losses were observed as 30% and 29% at 1 day testing whilst 6% and 22% strength losses were noted at 7 days for 30-RGS and 45-RGS mixes respectively. RGS mixes achieved either similar or slightly lower UCS values at 28 days. RGS mixes were observed to reduce as the curing age increases due to pozzolanic contribution by RGS.
- Schmidt hammer values showed similar trend as 28-days UCS results. Similar ratios for Schmidt hammer and 28-day UCS were reported for both strength classes. In addition, ratios between Schmidt hammer and 28-day UCS results were ranged between 0.44 and 0.50.
- 30-RGS provided higher UPV whereas lower UPV value was recorded for 45-RGS mix. Quite similar trend as UPV values were also noted by UCS and Schmidt hammer test results due to increased finer content provided better particle packing.
- Environmental sustainability results showed that RGS addition resulted in higher eCO_2 emissions due to longer transportation distance where RGS was obtained from. RGS indicated promising results in reducing the environmental footprint of concrete if obtained within 14.4 km radius. In addition, RGS also indicated promising result for economical sustainability by providing similar cost as conventional concretes. As far as the social sustainability concerned, RGS use may reduce the amount of waste sent to landfill and reduce the amount of natural raw materials used in concrete production.
- Potential use of RGS to improve sustainability credentials was investigated in this research. Environmental and economical sustainability need to be further investigated on RGS that is obtained from closer facilities. In addition, mechanical performance of RGS concrete having finer grading is also recommended for future studies in aiming to benefit more from amorphous phase of RGS and achieve similar mechanical performances with lower natural raw materials and cementitious contents.

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References

Adaway, M. & Wang, Y. (2015) Recycled glass as a partial replacement for fine aggregate in structural concrete – Effects on compressive strength. *Electronic Journal of Structural Engineering*. 14(1), 116-122.

Afshinnia, K. & Rangaraju, P.R. (2016) Impact of combined use of ground glass powder and crushed glass on selected properties of Portland cement concrete. *Construction and Building Materials*. 117, 263-272. https://doi.org/10.1016/j.conbuildmat.2016.04.072.

Alexander, M. & Mindness, S. (2010) *Aggregates in Concrete*. 1st Ed., CRC Press. ISBN: 9780415258395.

Arulrajah, A., Kua, T., Horpilbulsuk, S., Mirzababaei, M. & Chinkulkijniwat, A. (2017) Recycled glass as a supplementary filler material in spent coffee grounds geopolymers. *Construction and Building Materials*. 151, 18-27. http://dx.doi.org/10.1016/j.conbuildmat.2017.06.050.

Aydin, E. & Arel, H.Ş. (2019) High Volume Marble Substitution in Cement Paste: Towards Better Sustainability. *Journal of Cleaner Production*. Article in Press. https://doi.org/10.1016/j.jclepro.2019.117801.

Bilir, T., Yüksel, İ., Topçu, İ.B. & Gencel, O. (2015) Effects of bottom ash and granulated blast furnace slag as fine aggregate on abrasion resistance of concrete. 24(2), 261-269. https://doi.org/10.1515/secm-2015-0101.

Bostanci, S.C., Limbachiya, M.C. & Kew, H. (2018) Use of recycled aggregates for low carbon and cost effective concrete production. *Journal of Cleaner Production*. 189, 176-196. https://doi.org/10.1016/j.jclepro.2018.04.090.

Bourgiba, A., Ghorbel, E., Cristofol, L. & Dhaoui, W. (2017) Effect of recycled sand on the properties and durability of geopolymer and cement based mortars. *Construction and Building Materials*. 153, 44-54. http://dx.doi.org/10.1016/j.conbuildmat.2017.07.029.

Carsana, M., Frassoni, M. & Bertolini, M. (2014) Comparison of ground waste glass with other supplementary cementitious materials. *Cement & Concrete Composites*. 45, 39-45. http://dx.doi.org/10.1016/j.cemconcomp.2013.09.005.

Corinaldesi, V., Nardinocchi, A. & Donnini, J. (2016) Reuse of recycled glass in mortar manufacturing. *European Journal of Environmental and Civil Engineering*. 20, Issue sup1, 140-151. https://doi.org/10.1080/19648189.2016.1246695.

Demirel, B., Gultekin, E. & Alyamac, K.E. (2019) Performance of Structural Lightweight Concrete containing Metakaolin after Elevated Temperature. *KSCE Journal of Civil Engineering*. https://doi.org/10.1007/s12205-019-1192-x.

Du, H. & Tan, K.H. (2017) Properties of high volume glass powder concrete. *Cement & Concrete Composites*. 75, 22-29. http://dx.doi.org/10.1016/j.cemconcomp.2016.10.010.

European Parliamentary Research Service (2018) *CO_2 standards for new cars and vans*. PE 614.689. European Parliament.

Gagg, C.R. (2014) Cement and concrete as an engineering material: an historic appraisal and case study analysis. *Engineering Failure Analysis*. 40, 114-140. https://doi.org/10.1016/j.engfailanal.2014.02.004.

Gesoglu, M., Güneyisi, E., Hansu, O., Etli, S. & Alhassan, M. (2017) Mechanical and fracture characteristics of self-compacting concretes containing different percentage of plastic paste powder. *Construction and Building Materials*. 140, 562-569. https://doi.org/10.1016/j.conbuildmat.2017.02.139.

Guo, M.Z., Tu, Z., Poon, C.S. & Shi, C. (2018) Improvement of properties of architectural mortars prepared with 100% recycled glass by CO_2 curing. *Construction and Building Materials*. 179, 138-150. https://doi.org/10.1016/j.conbuildmat.2018.05.188.

Hajimohammadi, A., Ngo, T. & Kashani, A. (2018) Glass waste versus sand as aggregates: The characteristics of the evolving geopolymer binders. *Journal of Cleaner Production*. 193, 593-603. https://doi.org/10.1016/j.jclepro.2018.05.086.

Hajimohammadi, A., Ngo, T. & Kashani, A. (2018) Sustainable one-part geopolymer foams with glass fines versus sand as aggregates. *Construction and Building Materials*. 171, 223-231. https://doi.org/10.1016/j.conbuildmat.2018.03.120.

Harbi, R., Derable, R. & Nafa, Z. (2017) Improvement of the properties of a mortar with 5% kaolin fillers in sand combined with metakaolin, brick waste and glass powder in cement. *Construction and Building Materials*. 152, 632-641. http://dx.doi.org/10.1016/j.conbuildmat.2017.07.062.

Hilburg, J. (2019) *Archpaper.com* [online]. New York: The Architect`s Newspaper, LLC [cited 10th July 2019]. <https://archpaper.com/2019/01/concrete-production-eight-percent-co2-emissions/>.

Idir, R., Cyr, M. Tagnit-Hamou, A. (2011) Pozzolanic properties fine and coarse color-mixed glass cullet. *Cement & Concrete Composites.* 33(1), 19-29. https://doi.org/10.1016/j.cemconcomp.2010.09.013.

Ismail, Z.Z. & AL-Hashmi, E.A. (2009) Recycling of waste glass as a partial replacement for fine aggregate in concrete. *Waste Management*. 29, 655-59. http://doi:10.1016/j.wasman.2008.08.012.

Knoeri, C., Sanye-Mengual, E. & Althaus, H. (2013) Comparative LCA of recycled and conventional concrete for structural applications. *The International Journal of Life Cycle Assessment*. 18(5), 909-918. http://doi:10.1007/s11367-012-0544-2.

Limbachiya, M. (2009) Bulk engineering and durability properties of washed glass sand concrete. *Construction and Building Materials*. 23, pp.1078-1083. https://doi.org/10.1016/j.conbuildmat.2008.05.022.

Ling, T.C. & Poon, C.S. (2011) Utilization of recycled glass derived from cathode ray tube glass as fine aggregate in cement mortar. *Journal of Hazardous Materials*. 192(2), 451-456. https://doi.org/10.1016/j.jhazmat.2011.05.019.

Ling, T.C., Poon, C.S. & Kou, S.C. (2011) Feasibility of using recycled glass in architectural cement mortars. *Cement & Concrete Composites*. 33, 848-854. doi:10.1016/j.cemconcomp.2011.05.006.

Mineral Products Association (2019) *Sustainable Development Report 2018*. London: Mineral Products Association.

Nunes, S., Matos, A.M., Duarte, T., Figueiras, H. & Sousa-Coutinho, J. (2013) Mixture design of self-compacting glass mortar. *Cement & Concrete Composites*. 43, 1-11. https://doi.org/10.1016/j.cemconcomp.2013.05.009.

Özkan, Ö. & Yüksel, İ. (2008) Studies on mortars containing waste bottle glass and industrial by-products. *Construction and Building Materials*. 22, 1288-1298. doi:10.1016/j.conbuildmat.2007.01.015.

Paul, S.C., Savija, B. & Babafemi, A.J. (2018) A comprehensive review on mechanical and durability properties of cement-based materials containing waste recycled glass. *Journal of Cleaner Production*. 198, 891-906. https://doi.org/10.1016/j.jclepro.2018.07.095.

Penacho, P., de Brito, J. & Veiga, M.R. (2014) Physico-mechanical and performance characterization of mortars incorporating fine glass waste aggregate. *Cement & Concrete Composites*. 50, 47-59. http://dx.doi.org/10.1016/j.cemconcomp.2014.02.007.

Persistence Market Research (2019) *Persistence Market Research (PMR)* [online]. Persistence Market Research [cited 10th July 2019]. <https://www.persistencemarketresearch.com/market-research/global-construction-aggregates-market.asp>.

Rashid, K., Hameed, R., Ahmad, H.A., Razzaq, A., Ahmad, M. & Mahmood, A. (2018) Analytical framework for value added utilization of glass waste in concrete: Mechanical and environmental performance. *Waste Management*. 79, 312-323. https://doi.org/10.1016/j.wasman.2018.07.052.

Sadiqul Islam, G.M., Rahman, M.H. & Kayem, N. (2017) Waste glass powder as partial replacement of cement for sustainable concrete practice. *International Journal of Sustainable Built Environment*. 6, 37-44. http://dx.doi.org/10.1016/j.ijsbe.2016.10.005.

Siad, H., Lachemi, M., Sahmaran, M. & Anwar Hossain, K.M. (2017) Mechanical, Physical and Self-Healing Behaviors of Engineered Cementitious Composites with Glass Powder. 29(6). https://doi.org/10.1061/(ASCE)MT.1943-5533.0001864.

Siad, H., Lachemi, M., Sahmaran, M., Mesbah, H.A. & Anwar Hossain, K.M. (2018) Use of recycled glass powder to improve the performance properties of high volume fly ash-engineered cementitious composites. 163, 53-62. https://doi.org/10.1016/j.conbuildmat.2017.12.067.

Soliman, N.A. & Tagnit-Hamou, A. (2017) Using glass sand as an alternative for quartz in UHPC. *Construction and Building Materials*. 145, 243-252. https://doi.org/10.1016/j.conbuildmat.2017.03.187.

Tan, K.H. & Du, H. (2013) Use of waste glass as sand in mortar: Part I – Fresh, mechanical and durability properties. *Cement & Concrete Composites*. 35, 109-117. http://dx.doi.org/10.1016/j.cemconcomp.2012.08.028.

The Concrete Centre (2011) *Specifying Sustainable Concrete*. Ref. TCC/05/24, ISBN 978-1-908257-01-7; London: The Concrete Centre.

Uçal, G.O., Mahyar, M. & Tokyay, M. (2018) Hydration of alinite cement produced from soda waste sludge. *Construction and Building Materials*. 164, 178-184. https://doi.org/10.1016/j.conbuildmat.2017.12.196.

Ulubeyli, G.Ç., Bilir, T. & Artır, R. (2017) Ceramic Wastes Usage as Alternative Aggregate in Mortar and Concrete. *Periodicals of Engineering and Natural Sciences*. 5 (2), 194-201. http://dx.doi.org/10.21533/pen.v5i2.115.

Watts, J. (2019, February 25). Concrete: the most destructive material on earth. Retrieved from; https://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth.