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/mm² and 45 N/mm² 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 eCO₂ 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 Dönüşürlümsüz Cam Kumlu Betonun Mühendislik Özellikleri ve Sürdürülebilirlik Değerlendirmesi

Öz

Doğal hammaddede mevcudiyetindeki azalma, beton endüstrisini çevre dostu yaklaşımlar benimsemeye zorlamaktadır. Beton üretiminde geri dönüştürülümsüz malzemelerin kullanılması, beton üretiminin çevresel ayak izini azaltmak için popüler bir yaklaşımlı haline gelmiştir. Cam, kolayca toplanıp geri dönüştürülebilir en çok tüketilen malzemelerden biridir. Beton üretiminde cam kullanımı, beton üretiminde kullanılan doğal hammaddede miktarını potansiyel olarak azaltabilir ve atık gömme için kullanılan bakır arazilerinin depolama amacıyla kullanılmasını önler. Rapor edilen çalışma başlangıçta geri dönüştürülümsüz cam kumu kullanılarak üretilen betonun taze ve sertleşmiş performansını araştırılmış ve daha sonra da çevresel ve ekonomik sürdürülebilirlik açısından uygunluklarını değerlendirerek için sürdürülebilirlik analizi de yapılmıştır. Bu bağlamda, 30 N/mm² ve 45 N/mm² eşdeğer 28 günlük basınç dayanımına sahip kismen cam kumu ikame (ağrılıkça %10) edilerek yapılan betonlar oluşturulmuştur.

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Sustainable development requires that use of recycled or waste glass in concrete production is an environmentally friendly approach, concrete constituents should be locally available due to collection and transportation of these materials. Several waste materials have been utilized in either cement paste or concrete to determine 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 CO₂ 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 when 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, excluding 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 focuses 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 m²/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.

| Physical Properties (TS EN 1097, part 6) | Type of aggregates |
|------------------------------------------|--------------------|
|                                           | Gravel             | Sand               |
|                                           | Natural            | Recycled           |
| Unit weight (kg/m³)                      | 1.65               | 1.52               | 1.50               |
| Apparent density (kg/m³)                 | 2.76               | 2.71               | 2.61               |
| Water absorption capacity (%)            | 1.13               | 0.12               | 1.40               |
| Specific gravity                         | 2.74               | 2.69               | 2.59               |
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/mm². Mix designs were based on the relative density of the natural gravel. Concrete densities were kept constant as 2325 kg/m³ 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/mm² 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/m³) | Admixture |
|----------------|-------|-------------------------|-----------|
|                |       |                         | Natural   | RGS       |
|                |       | Water | PC  | Sand | Gavel | Admixture |
| 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 Assessment

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 Ready-mixed 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) |
|-----------|-----------------------------|----------------|
| 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](image)

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.

| Concrete Strength Class | Mix | Fresh Density (kg/m³) |
|-------------------------|-----|-----------------------|
| 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/m³) |
|-------------------------|-----|----------------------|
| 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.
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/mm²) |
|-------------------------|-------|------------------------|
| C30                     | NA    | 17.1                   |
|                         | RGS   | 17.5                   |
| C45                     | NA    | 20.7                   |
|                         | RGS   | 18.9                   |
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. eCO$_2$ emissions of concrete mixes

Figure 8. Percentage distribution of eCO$_2$ emissions of transportation and production of mixes

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

| Concrete mix | eCO$_2$ emission / 28-day UCS (kg CO$_2$ / N/mm$^2$) | Cost / 28-day UCS ($ / N/mm^2$) |
|--------------|---------------------------------------------------|-------------------------------|
| 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.
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 eCO₂ 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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