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Mechanical and Durability Properties of Green Star Concretes

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Abstract: This paper presents mechanical and durability properties of green star concretes. Four series of concretes are considered. The first series is control concrete containing 100% ordinary Portland cement, 100% natural aggregates and fresh water. The other three series of concretes are green star concretes according to Green Building Council Australia (GBCA), which contain blast furnace slag, recycled coarse aggregates and concrete wash water. In all above concretes compressive strength, indirect tensile strength, elastic modulus, water absorption, sorptivity and chloride permeability are measured at 7 and 28 days. Results show that mechanical properties of green star concretes are lower than the control concrete at both ages with significant improvement at 28 days. Similar results are also observed in water absorption, sorptivity and chloride permeability where all measured durability properties are lower in green star concretes compared to control concrete except the higher water absorption in some green star concretes.

Keywords: green star concrete; slag; recycled aggregate; wash water; sustainability

1. Introduction

Concrete is the most widely used construction materials in the world. Ordinary Portland cement (OPC) and aggregates are the important ingredients for concrete, where the former when mixed with water forms matrix which bind the aggregates and the latter contributes to the volume of the concrete. Ordinary concrete is not environmental friendly due to energy intensive manufacturing of OPC. It is reported that manufacturing of OPC contributes between 5 and 7% of global CO_2 emission and about one ton of CO_2 is released to produce the equal amount of OPC [1–3]. On the other hand, the aggregates which are sourced from various natural sources (e.g., river beds, rocks, sand dunes, etc.) also affects the natural eco-system. As a result, significant efforts are being directed to reduce the amount of OPC and natural aggregates in concrete to reduce the adverse impact on the environment. Significant research are also conducted to reduce the carbon footprint of concrete by partially replacing OPC and natural aggregates using various supplementary cementitious materials (SCMs) and recycled aggregates, respectively [4–9]. Among various SCMs fly ash, slag and silica fume, which are industrial by-products, are most widely used in concrete as partial replacement OPC. Recycled aggregates are sourced from crushed demolished concrete structures and are used as partial replacement of natural aggregates in concrete. A very good level of understanding exists on various properties of concretes containing SCMs and recycled aggregates either individually or combined through significant amount of research [10–16].

On the other hand, huge amount of tap water is used for washing activities in ready mix concrete plants. It is reported that about 500–1500 litres of tap water is used to wash one concrete mixer truck in the ready mix concrete plant [17]. Therefore, huge amount of clean water is being used in the concrete mixing plants. The reusing of this wash water in concrete mixing is the most sustainable way of reducing the use of clean tap water in concrete mixing facilities. Generally, the wash water from concrete mixing plants contains mostly cementitious fines and few chemicals from the use of superplasticizers, which are not different from the ingredients of concrete [17]. In a number of studies the effect of wash water and recycled water on the properties of concretes are studied and all are on concrete containing natural aggregates and OPC as the main binder [17–19].

Energy efficiency of buildings is another important requirement for asset owners, builders as well as the building regulators in many countries. Generally, the reduction of heating and cooling energy of buildings are the main objective in the design of energy efficient building. In one estimate it is found that built environment is world's single largest contributor of greenhouse gas and consumes about a third of water and generates 40% of wastes (Green Building Council Australia (GBCA)). To promote the environmental efficiency of buildings "green star" rating is introduced in many countries including in Australia, which is an internationally-recognized sustainability rating system for buildings. Among various green star points, up to three points are allocated for concrete. According to green building council of Australia [20] up to "two green star" points can be awarded to the concrete containing 40% SCMs as partial replacement of OPC, while up to "three green star" points can be awarded to concrete containing 40% SCMs as partial replacement of OPC, 40% recycled materials as partial replacement of natural aggregates and 50% reclaimed water as partial replacement of tap/drinking water. The above incentive encourages the promotion of environmentally friendly concrete in the construction of buildings.

Significant research has been devoted to study the properties of concrete containing partial replacement of OPC using various SCMs of various quantities and partial replacement of natural aggregates using various amounts of recycled concrete aggregates separately as well as their combined used. No study so far reported the properties of green star concretes where industrial by-products, recycled materials and reclaimed wash water are used together. This research presents the first study of this kind where mechanical and durability properties of green star concretes are studied and compared with control concrete containing 100% OPC, natural aggregates and fresh water.

2. Materials and Methods

In this study four series of mixes were considered. The first series was control concrete consisting of 100% OPC, 100% natural aggregates and 100% tap water. The second series was "two green star concrete" contained 40% slag (a by-product of steel industry) as partial replacement of OPC, while the rest of the materials were similar to the first series. The third series was similar to the second series except where 40% natural coarse aggregate (NCA) was replaced by recycled coarse aggregates (RCA) that were sourced from construction and demolition wastes. The fourth series was "three green star concrete" which was similar to the third series except where 50% fresh water was replaced by reclaimed wash water collected from the concrete laboratory. The fourth series was between two and three green star concrete and was considered to study the effect of 50% reclaimed wash water on the properties of three green star concrete. The mix proportions of all concretes are shown in Table 1. The percentage replacements of NCA by RCA and OPC by slag were on the basis of weight. The water/binder ratio was kept constant at 0.45 in all mixes. In all three types of green star concretes as well as control concrete mechanical properties in terms of compressive strength, elastic modulus and indirect tensile strength and durability properties in terms of sorptivity, water absorption and chloride permeability were measured at 7 and 28 days.

2.1. Materials

Ordinary Portland cement (OPC) was used in all concrete mixes. The blast furnace slag used in this study was obtained from a local supplier. The properties and chemical compositions of OPC and slag are shown in Table 2. The recycled coarse aggregate was obtained from a local construction and demolition (C&D) waste recycling plant in Perth, Western Australia. Figure 1 shows the analysis of 5 kg sample of the C&D waste used as RCA in this study. The percentages are based on mass. It can be seen that approximately 69% are from concrete and the rest consisted of limestone, masonry, etc. Table 3 shows the properties of recycled and natural aggregates. Sieve analysis of RCA is also conducted and about 23% were 20 mm size and 75% were 10 mm size. The natural coarse aggregates (NCA) used in this study were mixture of 10 mm and 20 mm sizes coarse aggregates at a ratio of 1:2. The NCA and RCA used in this study were in saturated and surface dry condition before used in the mixing. Chemical analysis of tap water and reclaimed wash water in concrete laboratory is shown in Table 4. It can be seen that the pH level of wash water is higher than that of tap water, while the turbidity of the wash water is much higher than the recommended limit for drinking water (5 NTU (Nephelometric Turbidity Unit)) by World health organization [21]. The higher turbidity in wash water can be attributed to various cementitious materials, superplasticizers and alkali chemicals used in the laboratory for the production of concrete and other cementitious materials.

Table 1. Mix proportion of concretes.

Series	Mix Proportions in Kg/m^3						
	OPC	Slag	Fine Aggregate	Natural Coarse Aggregate	Recycled Coarse Aggregate	Tap Water	Wash Water
Mix 1 (Control)	413	-	512	1254	-	190	-
Mix 2 (2 Green star)	248	165	512	1254	-	190	-
Mix 3	248	165	512	752	502	190	-
Mix 4 (3 Green star)	248	165	512	752	502	95	95

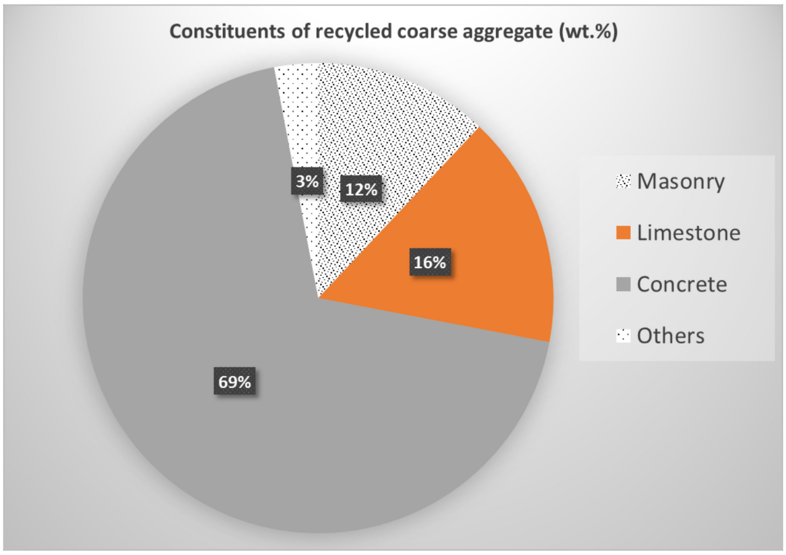


Figure 1. Analysis of construction and demolition wastes used as recycled coarse aggregates in this study.

Table 2. Chemical and physical properties of Ordinary Portland cement (OPC) and slag.

Chemical Analysis	OPC (wt %)	Slag (wt %)
SiO_2	21.1	32.45
Al_2O_3	5.24	13.56
Fe_2O_3	3.1	0.82
CaO	64.39	41.22
MgO	1.1	5.1
K_2O	0.57	0.35
Na_2O	0.23	0.27
SO_3	2.52	3.2
LOI	1.22	1.11
Specific gravity	3.17	3.00

Table 3. Properties of natural coarse aggregate (NCA) and recycled coarse aggregate (RCA).

Properties	NCA	RCA	NFA
Un-compacted bulk density (kg/m^3)	1547	1301	1498
Water absorption (%)	1.6	7.1	1.16

Table 4. Chemical analysis of tap water and wash water.

Chemical Properties	Tap Water	Wash Water
pH value	8.95	12.26
Chloride content (mg/L)	60	61
Turbidity (NTU)	-	41

2.2. Methods

The compressive strength, indirect tensile strength, elastic modulus, water absorption, water sorptivity and chloride ion permeability were measured at 7 and 28 days for all mixes. At least three specimens were cast and tested in each series for each property measured in this study. All specimens were water cured until the day before the test date. The compressive strength and elastic modulus tests were carried out on 100ø × 200 mm cylinders and the indirect tensile strength was determined on 150ø × 300 mm cylinders. The water absorption, water sorptivity and chloride ion permeability tests were conducted on 100ø × 50 mm thick specimens, which were made by cutting the standard 100ø × 200 mm cylinders. The compressive strength, indirect tensile strength and elastic modulus were measured according to the Australian standards AS1012.9 [22], AS1012.10 [23] and AS1012.17 [24], respectively. The concrete cylinders for the compressive strength and modulus of elasticity were sulphur capped to ensure a smooth surface. A MCC8 3000kN capacity machine was used to test the compressive strength and indirect tensile strength of all concrete samples. In the determination of modulus of elasticity a DMG/Rubicon 2500kN Universal Testing Machine was used to apply a constant load rate up to 40% of the ultimate load of respective concrete mix, while two linear variable differential transducers (LVDT) were used as shown in Figure 2 to measure the axial deformation of the cylinder. The slope of the recorded stress vs strain curve yielded the elastic modulus of the concrete.

Figure 2. Test setup to measure the elastic modulus of concrete cylinder.

The rate of water absorption (sorptivity) of concrete samples was measured according to ASTM C1585 [25]. The principle of the method is that a specimen had one surface in free contact with water (no more than 5 mm above the base of the specimen) while the other sides were sealed. This test determined the rate of absorption of water by hydraulic cement concrete by measuring the increase in the mass of a specimen resulting from absorption of water as a function of time. In this study the mass of the concrete specimen was measured regularly to determine the initial absorption from 1 min to the first 6 hours. The absorption *I* was the change in mass divided by the product of the cross-sectional area of the test specimen and the density of water. The initial rate of water absorption value (mm/sec$^{1/2}$) was calculated as the slope of the line that is the best fit to *I* plotted against the square root of time (sec$^{1/2}$). The chloride ion penetration resistance of concrete, popularly called the rapid chloride permeability test (RCPT), was conducted according to ASTM C1202 [26], details of which can be found in the standard. Water absorption of all concretes were measured according to the Australian standard AS1012.21 [27].

3. Results and Discussion

The workability of green star concretes in terms of measured slump values are shown in Figure 3 and is bench marked with respect to control concrete. It can be seen that the slump value of two green star concrete is higher than that of control concrete and can be attributed to the use of 40% slag as partial replacement of OPC. The relatively lower specific gravity of slag than that of cement increases the paste volume in concrete containing 40% slag, which cause the improvement in workability. The slump of mix 2 is decreased from 175 mm to 160 mm when 40% RCA is used as partial replacement of NCA in mix 3. This reduction can be attributed to the presence of 40% RCA whose water absorption is higher than NCA and contain more 10 mm size aggregates than the NCA. The workability is slightly affected in three green star concrete (mix 4) due to addition of 50% reclaimed wash water as partial replacement of tap water. High turbidity and pH of wash water are attributed to this slight reduction in workability. Nevertheless the workability of all green star concretes is better than the control concrete.

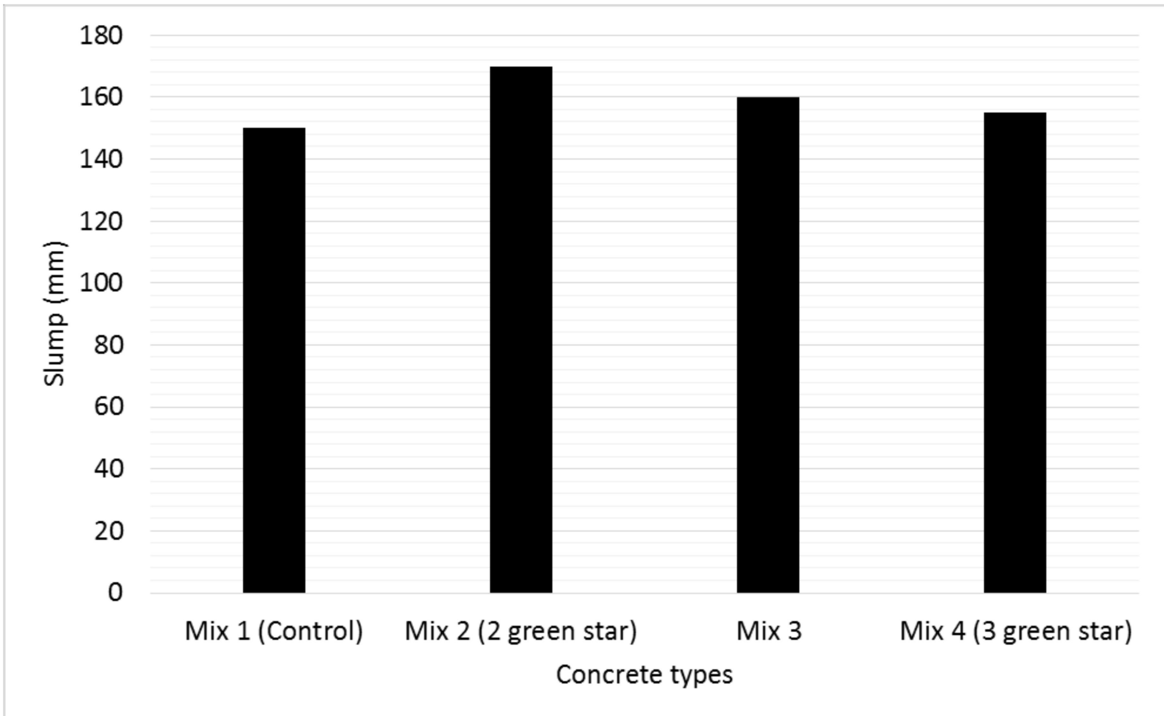


Figure 3. Measured slump values of green star concretes and control concrete.

The measured compressive strength of all concretes at 7 and 28 days are shown in Figure 4. It can be seen that the compressive strength of green star concretes is lower than the control concrete at both ages especially at 7 days. The partial replacement of OPC by 40% slag in two green star concrete exhibited about 31% and 12% reduction, respectively at 7 and 28 days compared to control concrete. The slow pozzalonic reaction of slag is the reason for higher compressive strength loss at 7 days in this concrete than at 28 days. However, when 40% RCA is used as partial replacement of NCA in mix 3 a slight reduction in both 7 and 28 days compressive strength is observed compared to mix 2. A slight reduction in both 7 and 28 days compressive strength is also observed in three green star concrete (Mix 4) when 50% wash water is used as partial replacement of tap water compared to Mix 3. The presence of weak interfacial transition zone between old mortar of RCA with new matrix and the higher turbidity of wash water could be the reason of the observed slight reduction in compressive strength in mixes 3 and 4 than mix 2. Nevertheless the three green star concrete containing 40% less OPC, 40% less NCA and 50% less fresh water exhibited a 28 days compressive strength of 38 MPa, which is 18% lower than the control concrete but still adequate enough for structural application. Similar reduction trend in indirect tensile strength and elastic modulus is also observed in all green star concretes compared to control concrete. It can be seen in Figures 5 and 6 that the reduction of indirect tensile strength of all green star concretes is slightly lower than that of compressive strength at both ages, however, in the case of elastic modulus the reduction was higher than the compressive strength. It is also interesting to observe that indirect tensile strength and elastic modulus of three green star concrete at both ages are similar and slightly higher, respectively than those of mix 3 concrete.

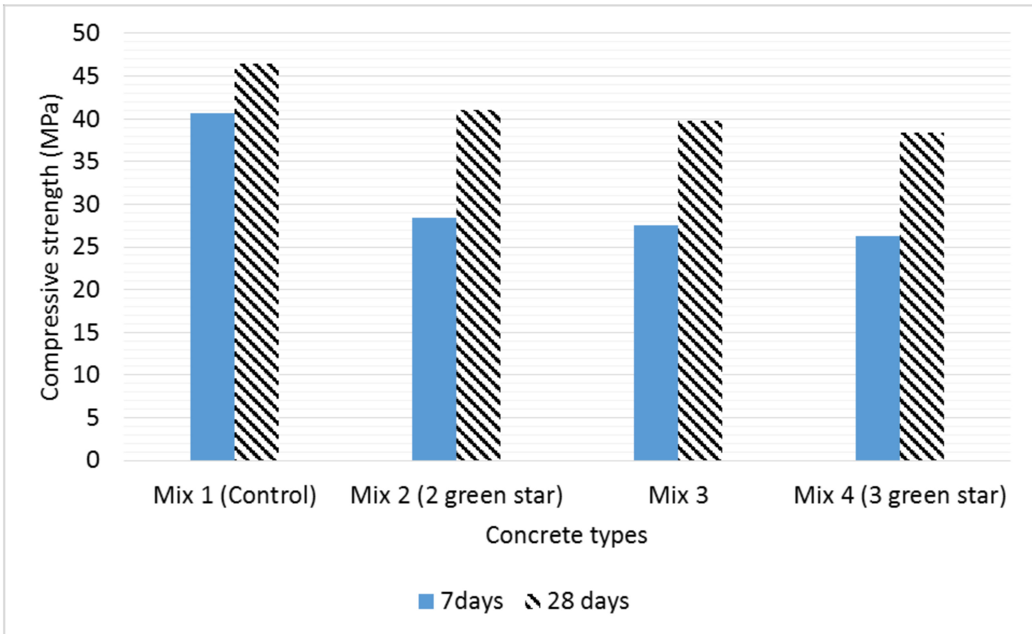


Figure 4. Measured compressive strength of green star concretes and control concrete.

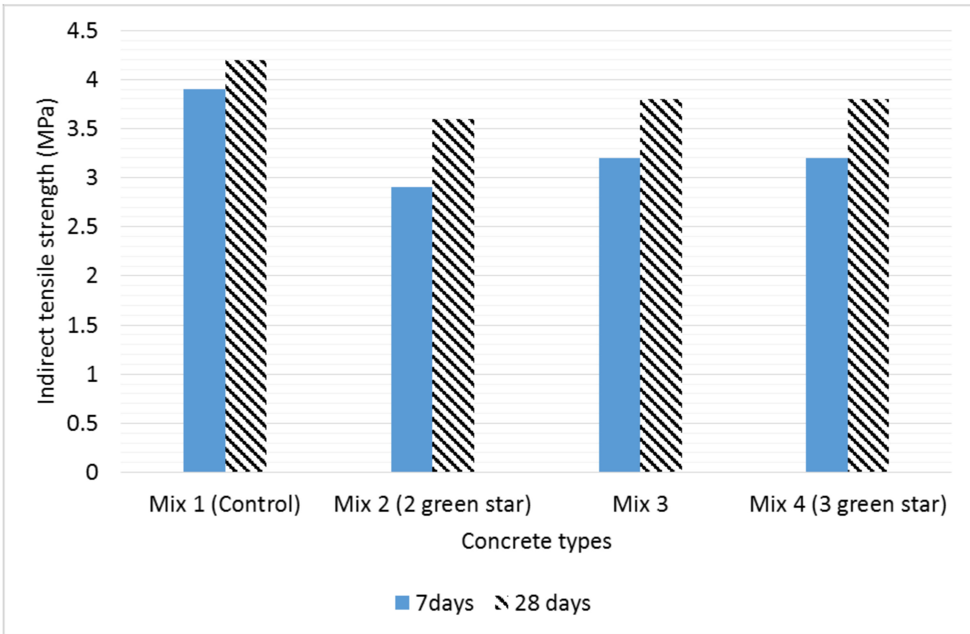


Figure 5. Measured indirect tensile strength of green star concretes and control concrete.

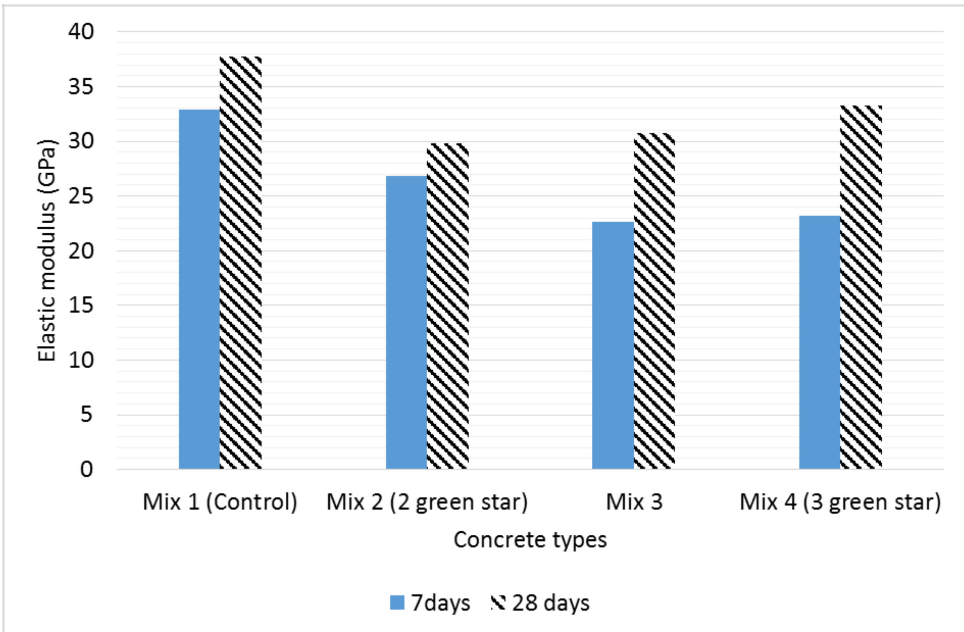


Figure 6. Measured elastic modulus of green star concretes and control concrete.

The measured durability properties of green star concretes are shown in Figures 7–10. Figure 7 shows the water absorption of green star concretes. No changes in water absorption of two green star concrete compared to control concrete after 7 days of wet curing can be seen, however, about 15% reduction is observed after 28 days curing. This can be attributed to the pozzolaanic reaction of SiO_2 and Al_2O_3 of slag with $Ca(OH)_2$ of hydration reaction which densified the matrix through formation of additional hydration products and pore filling by the slag particles. The three green star concrete and mix 3, as expected, showed much higher water absorption than control and two green star concretes due to the presence of 40% RCA, whose water absorption capacity is much higher than NCA as shown in Table 3. The effect of wash water however is not affected the water absorption of three green star concrete than of mix 3 concrete. Unlike water absorption, the rate of water absorption of all green star concretes is lower than that of control concrete at both ages. Among green star concretes, the two green star concrete containing 40% slag as partial replacement of OPC exhibited the lowest rate of water absorption at both ages and is believed to be due to the pore refinement of its matrix due to additional hydration product formed through pozzolanic reaction and pore filling. After 28 days of curing this rate further reduced. A summary of water sorptivity, which is the slope of the rate of water absorption lines in Figure 8, is shown in Figure 9. It can be seen that the sorptivity of mix 3 and mix 4 concretes is very similar, where no adverse effect of wash water on sorptivity is observed in three green star concrete. Similar result is also observed in chloride ion penetration in green star concretes in RCPT test. It can be seen in Figure 10 that the chloride permeability in two green star concrete is significantly reduced by 62% after 28 days of wet curing. This can be contributed by the pore refinement of matrix in two green star concrete due to pozzolanic reaction of slag and pore filling. However, after 7 days of curing the reduction in chloride permeability is much lower than that at 28 days due to slow pozzolanic reaction of slag. The addition of 40% RCA in mix 3 concrete, however, increased the chloride permeability possibly due to higher porosity of RCA than NCA and the presence of more interfacial transition zone with matrix and RCA than with matrix and NCA. Interestingly, the three green star concrete shows lower chloride permeability than the other two green concrete mixes, which is not observed in water absorption and sorptivity tests, where a slight increase in water absorption and sorptivity is observed in three green star concrete than mix 3. While all three measured durability properties are affected by the pores in the concrete, the water absorption and sorptivity are mostly depend on overall porosity of the concrete as the specimens in those tests are kept in water or in contact with water for long time. However, in RCPT test Cl^- is forced to pass from one side of the concrete specimen to other side. Therefore, the observed lower chloride ion penetration in three green star concrete than other two green star concretes indicate that the pores in that concrete are not interconnected rather disperse.

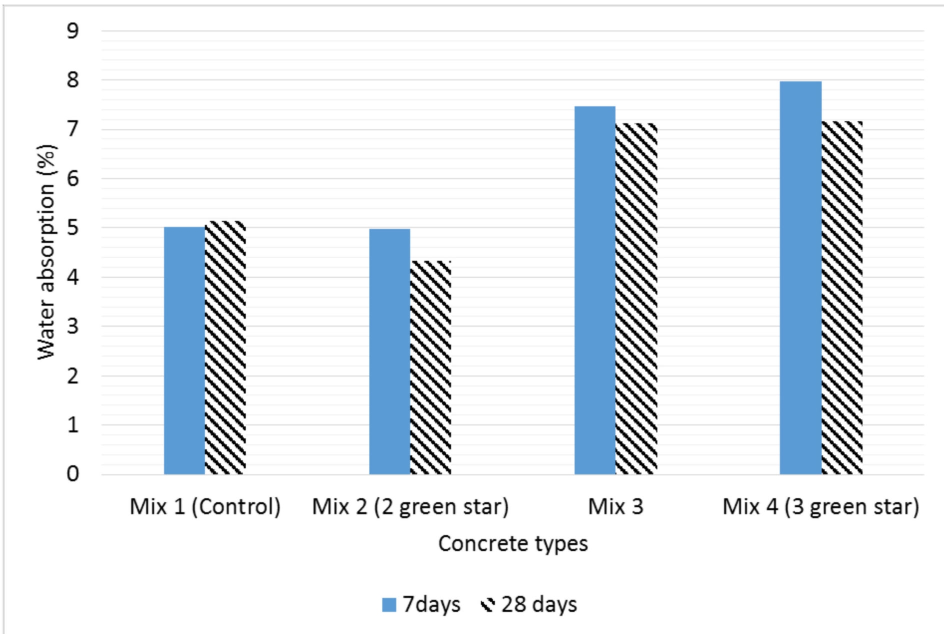
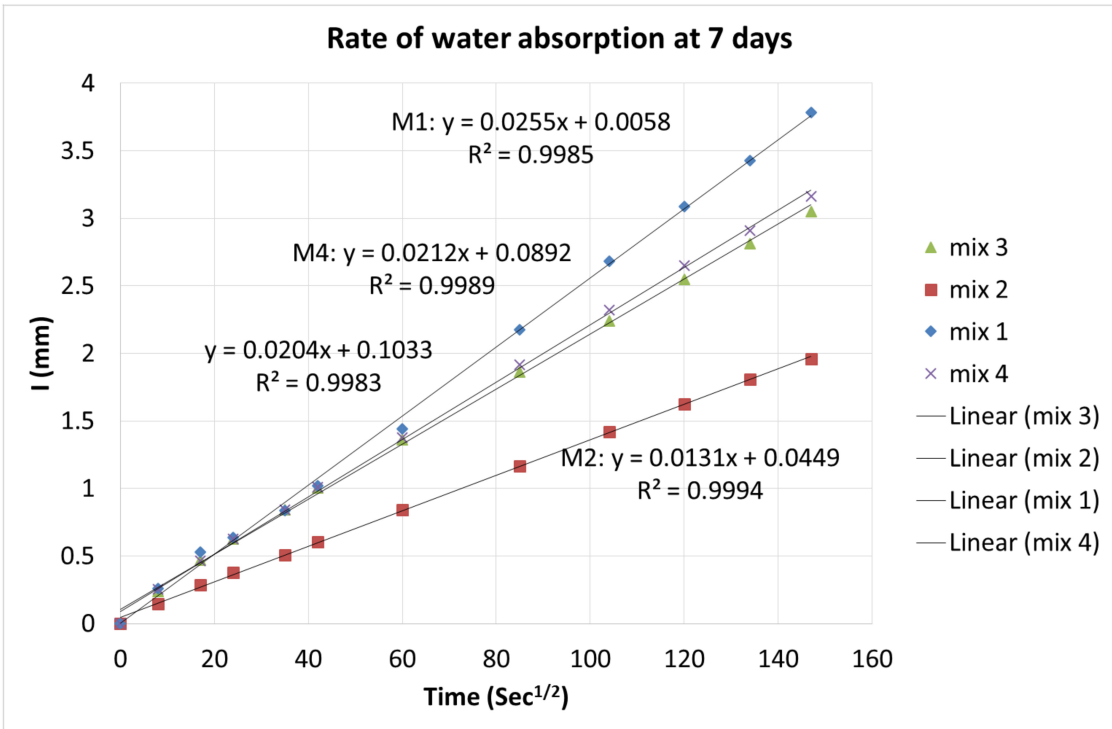
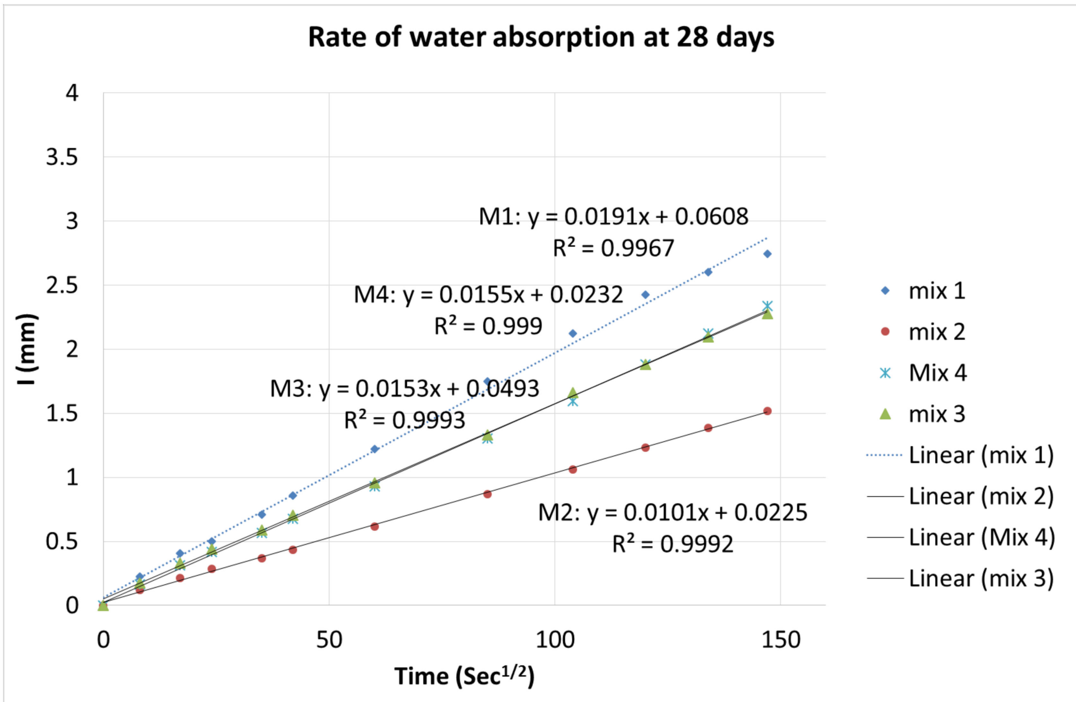


Figure 7. Measured water absorption of green star concretes and control concrete.



(**a**)



(**b**)

Figure 8. Rate of water absorption of green star concretes and control concrete at (**a**) 7 days and (**b**) 28 days.

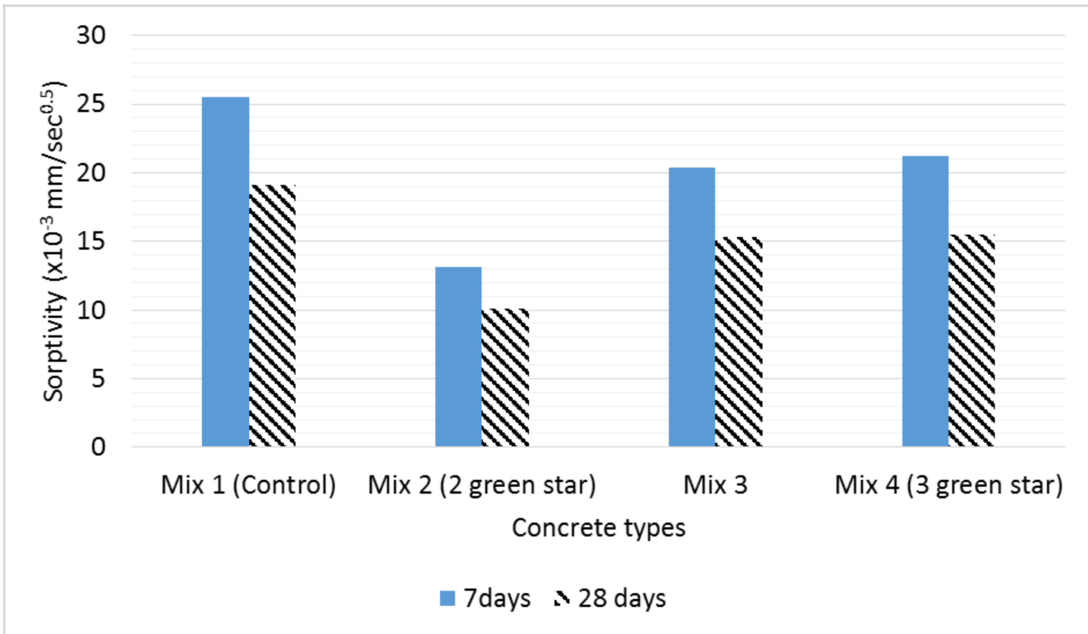


Figure 9. Summary of sorptivity of green star concretes and control concrete.

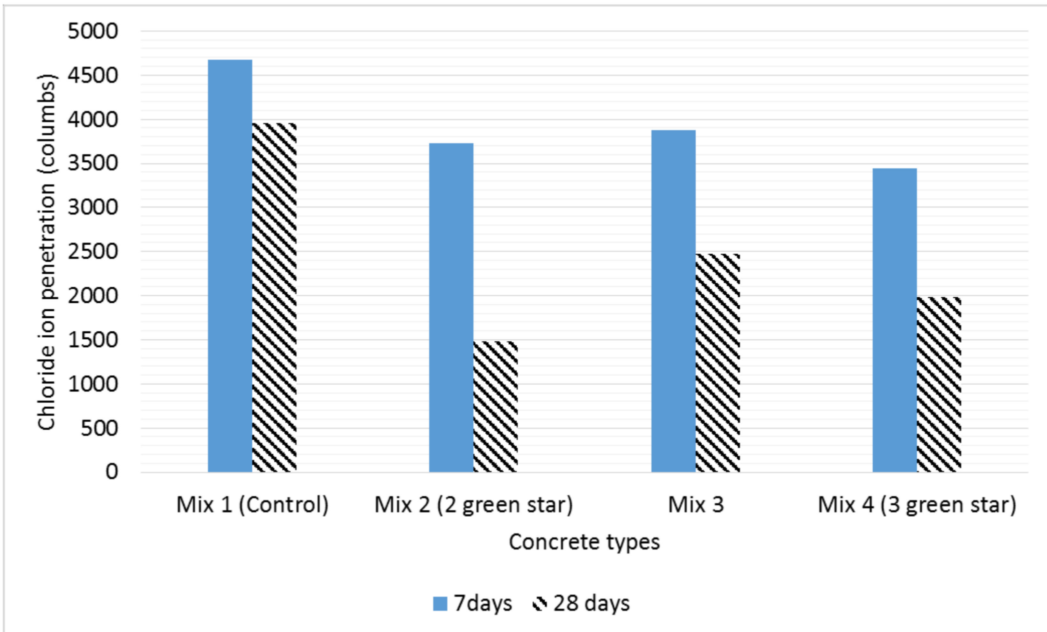


Figure 10. Measured chloride ion prenetration of green star concretes and control concrete.

4. Conclusions

This study evaluated mechanical and durability properties of green star concretes according to the definition of green building council Australia and bench marked with control concrete. Within limited studies the following conclusions can be drawn:

- Green star concretes exhibited reduction in compressive strength, indirect tensile strength and elastic modulus at both 7 and 28 days compared to control concrete. However, the reduction at 7 days of green star concrete is much higher than at 28 days. Formation of additional hydration products and particle packing due to pozzolianic reaction and small particle size of slag are contributed to the increase in above mechanical properties at 28 days. Three green star concrete exhibited about 18%, 10% and 12% reduction in compressive strength, indirect tensile strength and elastic modulus, respectively at 28 days compared to control concrete while containing 40% less OPC, 40% less NCA and 50% less fresh water.

- The two green star concrete containing 40% slag exhibited lower water absorption, sorptivity and chloride permeability than control concrete at both ages, while three green star concrete containing 40% slag, 40% RCA and 50% concrete wash water exhibited better durability properties at both ages except the water absorption which is about 25% higher than two green star concrete at 28 days. The presence of 40% RCA, whose water absorption capacity is much higher than the NCA, is the reason for such increase in water absorption.
- Both two and three green star concretes exhibited 28 days compressive strength of about 40 MPa and much lower chloride permeability than control concrete. Therefore, these green concretes can be used in structural application with good resistance against reinforcement corrosion.

While only slag and concrete wash water are used to partially replace the OPC and tap water, respectively in the green star concretes in this study, other SCMs. E.g., fly ash, silica fume, combination of fly ash/slag/silica fume and recycled water from other sources can be used in green star concretes and studied their properties to establish their use.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Moretti, L.; Caro, S. Critical analysis of the life cycle assessment of the Italian cement industry. *J. Cleaner Prod.* **2017**, *152*, 198–210. [CrossRef]
2. Limbachiya, M.; Bostanci, S.C.; Kew, H. Suitability of BS EN197 CEM II and CEM V cement for production of low carbon concrete. *Constr. Build. Mater.* **2014**, *71*, 397–405. [CrossRef]
3. Malhotra, V.M. Sustainable development and concrete technology. *Concr. Int.* **2002**, *24*, 1–22.
4. Malhotra, V.M.; Mehta, P.K. *High-Performance, High-Volume Fly Ash Concrete: Materials, Mixture Proportioning, Properties, Construction Practice, and Case Histories*; HVFA High-Performance-Inc.: Ottawa, ON, Canada, 2002.
5. Siddique, R. Performance characteristics of high-volume class F fly ash concrete. *Cem. Concr. Res.* **2004**, *34*, 487–493. [CrossRef]
6. Kou, S.C.; Poon, C.S.; Chan, D. Influence of fly ash as a cement addition on the hardened properties of recycled aggregate concrete. *Mater. Struct.* **2007**, *41*, 1191–1201. [CrossRef]
7. Shaikh, F.U.A.; Supit, S.W.M. Compressive strength and durability properties of high volume fly ash concretes containing ultrafine fly ash. *Constr. Build. Mater.* **2015**, *82*, 192–205. [CrossRef]
8. Berndt, M.L. Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate. *Constr. Build Mater.* **2009**, *23*, 2606–2613. [CrossRef]
9. Corinaldesi, V.; Moriconi, G. Influence of mineral additions on the performance of 100% recycled aggregate concrete. *Constr. Build. Mater.* **2009**, *23*, 2869–2876. [CrossRef]
10. Poon, C.S.; Shui, Z.H.; Lam, L. Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates. *Constr. Build. Mater.* **2004**, *18*, 461–468. [CrossRef]
11. Sagoe-Crentsil, K.K.; Brown, T.; Taylor, A.H. Performance of concrete made with commercially produced coarse recycled concrete aggregate. *Cement Concr. Res.* **2001**, *31*, 707–712. [CrossRef]
12. Ahmed, S.F.U. Properties of concrete containing construction and demolition wastes and fly ash. *J. Mater. Civ. Eng.* **2013**, *25*, 1864–1870. [CrossRef]
13. Ahmed, S.F.U. Properties of concrete containing recycled fine aggregate and fly ash. *J. Solid Waste Technol. Manage.* **2014**, *40*, 70–78. [CrossRef]
14. Shaikh, F.U.A.; Odoh, H.; Than, A.B. Effect of nano silica on properties of concrete containing recycled coarse aggregates. *Constr. Mater.* **2014**, *168*, 68–76. [CrossRef]

15. Shaikh, F.U.A. Effect of ultrafine fly ash on properties of concretes containing construction and demolition wastes as coarse aggregates. *Struct. Concr.* **2016**, *17*, 116–122. [CrossRef]
16. Zhang, W.; Ingham, J.M. Using recycled concrete aggregates in New Zealand ready-mix concrete production. *J. Mater. Civ. Eng.* **2010**, *22*, 443–450. [CrossRef]
17. Kadir, A.A.; Shahidan, S.; Yee, L.H.; Hassan, M.I.H.; Abdullah, M.A. The effect on slurry water as a fresh water replacement in concrete properties. *IOP Conf. Ser. Mater. Sci. Eng.* **2016**, *133*, 012041. [CrossRef]
18. Al-jabri, K.S.; Al-saidy, A.H.; Taha, R.; Al-kemyani, A.J. Effect of using waste water on the properties of high strength concrete. *Procedia Eng.* **2011**, *14*, 370–376. [CrossRef]
19. Lobo, C.; Mullings, G.M. Recycled water in ready mixed concrete operations. *Concr. Focus* **2003**, *2*, 1–10.
20. Revised Green Star Concrete Credit, Green Building Council Australia. Available online: https://www.gbca.org.au/green-star/materials-category/revised-green-star-concrete-credit/34008.htm (accessed on 30 October 2017).
21. Water Research Centre National Secondary Drinking Water Standards. Available online: https://www.water-research.net/index.php/standards/secondary-standards (accessed on 9 July 2018).
22. AS 1012.9. *Determination of Compressive Strength of Concrete*; Australia Standards: Sydney, Australia, 2010.
23. AS 1012.10. *Determination of Indirect Tensile Strength of Concrete*; Australia Standards: Sydney, Australia, 2010.
24. AS 1012.17. *Determination of Elastic Modulus of Concrete*; Australia Standards: Sydney, Australia, 2010.
25. ASTM C1585-13. *Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic Cement Concretes*; ASTM International: West Conshohocken, PA, USA, 2013.
26. ASTM C1202. *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride ion Penetration*; American Society for Testing and Materials: Philadelphia, PA, USA, 2012.
27. AS 1012.21. *Determination of Water Absorption and Apparent Volume of Permeable Voids in Hardened Concrete*; Australia Standards: Sydney, Australia, 1999.

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