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Development of Self-Cured Sustainable Concrete Using Local Water-Entrainment Aggregates of Vesicular Basalt

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Abstract: The environmental and economic concerns pertaining to the construction industry have necessitated the development of sustainable concrete. Durability and strength are the two primary properties which determine the sustainability of concrete. This study evaluated the performance of self-cured concrete produced from local vesicular basalt porous aggregates. The durability indicators, porosity, permeability and pore size of the hardened concrete, were obtained from the water sorptivity (water permeability under capillary action) test, the water permeability under pressure action test and the Brunauer–Emmett–Teller (BET) surface area test and strength was evaluated in terms of compressive strength of concrete. The concrete specimens were produced with 10% porous vesicular basalt aggregate in replacement of coarse aggregate. The concrete specimens were tested at 3, 7 and 28 days. The self-curing effect on concrete strength was evaluated against water, air and membrane cured specimens, at surface/volume ratio of 26.4/40 and w/c ratio of 0.35/0.5. A 20% decrease in sorptivity coefficient, 10% increase in solid surface area and about 10% increase in compressive strength of the self-cured concrete was observed over the conventionally cured concrete. The study concludes that the addition of water-entrainment aggregates to concrete reduces water permeability, results in a finer pore structure of concrete and increases the quality and durability of concrete.

Keywords: curing; microstructure; durability; water-entrainment aggregate; sustainability; self-curing

Citation: Ahmed, M.; AlQadhi, S.; Alsulamy, S.; Islam, S.; Khan, R.A.; Danish, M.. Development of Self-Cured Sustainable Concrete Using Local Water-Entrainment Aggregates of Vesicular Basalt. *Sustainability* **2021**, *13*, 6756. https://doi.org/10.3390/su13126756

Academic Editors: Adil Saeed and Shagufta Khan

Received: 24 May 2021
Accepted: 10 June 2021
Published: 15 June 2021

1. Introduction

Sustainable concrete can be developed through the selection of a sustainable production process and sustainable concrete ingredient materials, satisfying the environmental and socio-economic aspects of sustainability. Curing, an important process in concrete casting, is the method of regulating the rate and extent of concrete moisture loss, both in depth and near the surface, during the hydration of cement. Curing is carried out by external water-adding techniques, such as ponding, water spray and wet hessian, and by external water-retaining techniques, such as draping with plastic sheeting, late removal of formwork and application of curing membranes. The conventional curing methods, such as the water curing method, are not very effective and sustainable for high performance concrete and for the durability of concrete requiring reduced porosity and water permeability. In other words, the conventional curing method is not resource-effective and cost-effective enough to produce sustainable concrete. In addition, the conventional curing method, or water curing, is not a suitable curing method from a sustainability point of view, for concrete containing supplementary cementitious materials requires longer curing times (slower reactions). The self-curing, or internal-curing, method enables the curing of concrete both at depth and near the surface of concrete, for the proper development of strength and durability characteristics of different types of concrete. The self-curing method, using local water-entrainment aggregates, has the prospect and potentiality for the development of sustainable concrete. The porous water-entrainment aggregates operate as internal water reservoirs in the concrete, allowing the compensation of the evaporated water present in the water-entrainment aggregates to prevent the shrinkage of the concrete. Moreover, the water-entrainment aggregates in self-cured concrete permit a controlled formation of water-filled macropore inclusions in the fresh concrete to aid the cement hydration process and gradually release water to hydrate un-hydrated cement particles within the matrix. The water-entrainment aggregates of self-curing concrete also help to avoid the formation of cracks in concrete with a continued hydration process and can act as an admixture to self-healing concrete, which is a concrete with the ability to repair its cracks autogenously or autonomously. Wasiu et al. [1] have highlighted that the various structural failures recorded around the world are due to non-adherence to good concrete construction practice. The self-curing method can be utilized to mitigate the effect of extreme environmental conditions on concrete [2–4]. The advantages and awareness of the overall benefits of the self-curing method are reviewed by Nduka et al. [5]. They found that concrete stakeholders have not fully exploited the benefits of the self-curing method and found scarce application in practice. The evolution of self-curing concrete is explained through the case studies by Roberts et al. [6]. Yang et al. [7] have presented a review on the factors affecting the effectiveness of self-curing. Their review includes factors such as the amount of self-curing water, characteristics of self-curing materials and migration distance of self-curing water. Research works are reported to develop concrete design methods [8–13] and specifications [14–17] for self-cured and sustainable concrete production. The literature related to shrinkage properties of self-cured concrete has been surveyed by Liu et al. [18]. Weiss and Morian [19] have reviewed the application of the self-curing method in concrete pavement. Cusson et al. [20] and Vosoughi et al. [21] studied the effects of the self-curing method on concrete service life and concrete life-cycle costs. They have concluded that self-curing improved the service life of the structure and resulted in 38% lower life-cycle costs.

Tia et al. [22] have ascertained the usability of self-cured concrete using lightweight aggregates for bridge decks and concrete pavement slabs through laboratory analysis and a field-testing program conducted on test slabs. A project management five-dimensional framework analysis, in categories of context, scheduling, costs, technique and finance, has been carried out by Daghighi [23] to evaluate the advantages and disadvantages of lightweight fine aggregate (LWFA) self-cured concrete and normal plain concrete in concrete paving methods. The cost and finance analysis presented the disadvantage in using LWFA due to increased initial costs and advantage due to decreased total life-cycle costs. The scheduling and technical analyses showed the disadvantage in using LWFA due to increased complexity level of the project and possible challenges in developing a mixture design. A multicriteria decision making (MCDM) technique, based on the Technique of Order Preference Similarity to the Ideal Solution (TOPSIS) methodology, is applied by Ahmed et al. [24] for sustainable concrete quality management, by selecting the most appropriate concrete mixture factors and mixture design method.

There has been interest in exploring the mechanisms of self-curing concrete that cause the enhancement of microstructure, physical, mechanical and durability properties. A method is proposed by Johansen et al. [25] to determine the absorption capacity of self-curing agents in concrete. The water travel distance zone of water-entrainment agents in self-curing concrete is studied by Zhutovsky et al. [26]. Ackay and Tasdemir [27] have investigated the influence of the distribution of lightweight aggregates on self-curing concrete. A test procedure is developed by Bello et al. [28] to estimate the water absorption/desorption of lightweight aggregates in self-cured concrete. The application of the self-curing approach to concrete results in lower voids and more compact concrete [29]. Self-curing concrete improves the interface transition zones microstructure and strength with less porosity [30]. The type, amount and particle size of curing agents influence self-curing efficiency, as well as the permeability of the cement paste matrix. Paul et al. [31] found, from the investigation oon self-curing concrete using lightweight aggregates of different internal structures and different size distributions, that the water transport mechanism in self-curing is controlled by capillary action and air diffusion into the pore water.

Jensen and Hansen [32] proposed a concept to prevent the self-desiccation in concrete using water-entrainment superabsorbent polymers (SAP). Gupta and Kua [33] studied the effect of water entrainment by pre-soaked biochar particles on strength and permeability of cement mortar. Researchers have attempted to use a number of materials as self-curing concrete, with improved behavior as compared to concrete with conventional curing and found that the optimum amount of curing materials relies on the type of curing agent and grade of concrete. The behavior of self-curing concrete with various curing agents is reviewed by Memon et al. [34] and they categorized the self-curing agent reported in research as natural dependent, artificial, recycled, or chemical. A state-of-the-art review report on the use of SAP as water-entrainment agents in concrete construction is compiled by RILEM [35]. The studies on concrete using different types of aggregates as self-curing agents are listed in Table 1.

Table 1. Types of self-curing agents.

Self-Curing Agent and Type	Study Contribution	Reference
Normal weight porous aggregate (natural)	Shrinkage and strength properties of mortars	Zou et al. [36]
Pumice light weight aggregate (natural)	Durability and micro-structural properties of self-compacting concrete (SCC)	Khotbehsara et al. [37]
Recycled concrete aggregate (recycled)	Eco-efficiency indexes (bi and ci), as well as the eco-durability ($S\text{-}CO_2$) index of concrete made with normal and blast-furnace slag cement	Grabiec et al. [38]
Porous ceramic waste aggregates (recycled)	Shrinkage and early age cracking of concrete	Suzuki et al. [39]
Biomass derived waste LWA (recycled)	Pore structure, water absorption and desorption behavior of aggregates, shrinkage properties of concrete	Lura et al. [40]
Lightweight expanded clay aggregates (LECA) (natural)	Effect on pH, mass loss, volumetric water absorption on concrete and strength, durability properties of concrete	Mousa et al. [41]
Zeolite aggregates (natural)	Micro-structural, water absorption and desorption of aggregate and shrinkage, mass loss of concrete	Ghourchian et al. [42]
Wood derived aggregates (natural, chemical)	Interfacial transition zone, nano-mechanical properties	Zadeh and Bobko [43]
Paraffin wax (chemical)	Permeability and resistance to abrasion properties	Chand et al. [44]
Super absorbent polymers (SAP) (artificial)	Effect of heat treatment on shrinkage characteristics	Kang et al. [45]
Lechugilla fiber (natural)	Setting time, mechanical properties, shrinkage, durability properties	Davila-Pompermayer et al. [46]
Bentonite clay (natural)	Micro-structural, water absorption, shrinkage and strength properties of concrete	Lura and Kovler [47]
Diatomaceous earth (natural)	Micro-structural, water absorption, shrinkage and strength properties of concrete	Lura and Kovler [47]
Perlite (natural)	Micro-structural, water absorption, shrinkage and strength properties of concrete	Lura and Kovler [47]
Polyethylene-glycol (artificial)	Mechanical properties of concrete	Francis et al. [48]
Crushed over burnt clay bricks (artificial)	Mechanical properties of concrete	Rashwan et al. [49]
Fly ash and query dust (binary, natural)	Mechanical properties of concrete	Revalty and Lakashimi [50]
Rice husk ash (recycled)	Porous surface structure and pore size distribution of aggregates, portlandite content, flowability of concrete	Rößler et al. [51]
Coal bottom ash reactive aggregate (recycled)	Porosity, sphericity, water absorption and water desorption of aggregate	Balapour et al. [52]
Cenospheres (recycled)	Autogenous shrinkage and strength of mortars	Liu et al. [53]
Drinking water treatment waste (recycled)	Degree of hydration and strength properties of concrete	Nowasell and Kevern [54]

The rate of flow of water in concrete pores, i.e., sorptivity of concrete, is correlated by Hanif et al. [55], with the eco-durability ($S\text{-}CO_2$ index) of concrete materials. Shannag et al. [56] have used volcanic scoria rocks aggregates of north-western Saudi Arabia for developing structural lightweight concrete and studied the physical, mechanical and durability characteristics of lightweight concrete. De la Varga et al. [57] have proposed self-curing with the addition of fly ash and other pozzolanic additives in concrete to reduce the effects of adverse environmental conditions on concrete. The influence of self-curing and water–cement ratio on shrinkage-induced cracking in self-cured concrete is investigated by Zhang et al. [58]. The early-age tensile creep and cracking potential of self-cured concrete is estimated by Shen et al. [59]. Zang et al. [60] have developed a mathematical model based on the finite differential method to simulate the concrete moisture field with pre-soaked lightweight aggregate blending and to predict the moisture variations with time in self-cured concrete.

The self-curing, in addition to the conventional method of curing, or external curing method, is needed for curing, as cement hydration requires a continuous supply of water, both externally and internally, for the proper development of the strength and durability properties of concrete. The locally available water-entrainment aggregates of vesicular basalt, which give greater strength and durability to self-cured concrete, satisfy the socio-economic and environmental aspects of sustainability, as concrete has the proper resource utilization, improvement of quality of life (long life, lower CO_2 emission and material wastage), reduction in costs (less water usage and maintenance) and increased economic activity in society for concrete production. The quantitative evaluation of the environmental and socio-economic sustainability indicators, i.e., strength and durability of self-cured concrete, is carried out in this study. The mechanical and durability properties of self-curing concrete by inclusion of water-entrainment aggregates (vesicular basalt) are assessed in terms of compressive strength, microstructure and water permeability, including the pore structure of concrete. The study also explores the performance of concrete under various curing conditions, curing durations, water–cement ratio and concrete surface area–concrete volume ratio. The performance of the self-curing method with other types of conventional curing methods is compared to qualify local water-entrainment aggregate-based self-cured concrete as sustainable concrete.

2. Experimental Methodology

A detailed experimental program has been planned in this study to investigate the effects of the self-curing method on the durability and mechanical properties of concrete prepared from the local water-entrainment aggregates and other materials. The porous aggregate of vesicular basalt was introduced in the concrete mix at 10% by weight of coarse aggregates by replacing the coarse aggregate. Silica fume at 12% was used as a partial replacement for cement on equal weight basis. The two water–cement (binder) ratios, at 0.35 and 0.5, were chosen to develop a concrete strength of 30–50 MPa. For lower water cement ratio, a superplasticizer was added to increase the workability. Two types of concrete specimens were casted using steel molds of 150 × 150 × 150 mm cubes and 150 × 300 mm cylinders. The specimens were taken out from the molds after 24 h of casting at laboratory environment (26 + 2 °C and 65 + 5 relative humidity) and cured under different conditions until testing. Four types of curing conditions, namely, water curing, air curing, membrane curing and self-curing method, were used for the concrete specimens. Standard cylinders and cube specimens were tested under uniaxial compression. The specimens were tested after 3, 7 and 28 days of curing. The durability characteristics of concrete were assessed using the three test methods, namely, the sorptivity test, the water permeability test and the Brunauer–Emmett–Teller (BET) surface area test, in terms of pore structure and permeability of the hardened concrete. Partial water curing is important in self-curing concrete to prevent surface cracking due to drying shrinkage [61] and a minimum of 3 days partial water curing was selected in this study [62]. The normal concrete was water-cured for 28 days, while concrete made from water-entrainment aggregates was water-cured for 3 days and 28 days, for durability testing, i.e., sorptivity and pore size. Water curing of concrete was considered as control curing. Three identical specimens were tested for various curing methods and different durations of curing.

2.1. Materials and Concrete Mixture

2.1.1. Concrete Ingredients

Ordinary Portland cement (Type-I) was utilized in the present study. The mechanical and chemical properties of cement are given in Table 2. The properties of fine aggregate and coarse aggregate (20 mm maximum size) are given in Table 3. Silica fumes, with fineness in terms of specific surface of 20,000 m^2/kg, were used for achieving high strength in concrete. Table 4 gives the chemical composition of the silica fumes used in the sample. High performance super-plasticizing admixture Conplast SP430, product of Fosroc International Limited, brown in color, compliant with ASTM C494 [63], having specific gravity of 1.185 at 20 °C, was used. Conplast SP430 is chloride free and uses less than 72.0 g Na_2O equivalent/liter of admixture. The dosage of Conplast SP430 used in the present study was 1 L per 100 kg of concrete. For both mixing and curing concrete, municipality supplied water was used.

Table 2. Mineral composition, mechanical and chemical properties of cement.

Chemical Properties		**Mineral Composition/Strength**	
Constituents	**Quantity (%)**	**Constituents/Modulus/Strength**	**Quantity/Value**
SiO_2	21.30	C_3S	51.43%
Al_2O_3	4.86	C_2S	22.27%
Fe_2O_3	5.79	C_3A	3.08%
CaO	63.74	C_4AF	17.92%
MgO	1.37	Alkali as Na_2O	0.45%
SO_3	1.84	Lime silica modulus	90.33
K_2O	0.44	Silica modulus	2.00
Na_2O	0.15	Alumina modulus	0.84
LOI	1.10	Compressive strength, (3 days)	18.51 MPa
Insoluble residue	0.41	Compressive strength, (7 days)	23.45 MPa
Free CaO	1.08		

Table 3. Properties of aggregates.

Aggregates Type	**Source**	**Specific Gravity**	**Fineness Modulus**
Fine aggregate	Sandstone	2.6	3.3
Coarse aggregate	Basalt	2.7	7.097

Table 4. Chemical composition of silica fume.

Constituent	**Fe_2O_3**	**Al_2O_3**	**SiO_2**	**LOI**	**CaO**
Quantity (in %)	2.110	0.390	91.030	4.050	1.500

2.1.2. Water-Entrainment Aggregates for Self-Curing (Vesicular Basalt)

The self-curing agent, namely, normal weight porous vesicular basalt aggregates from the north–western region of Saudi Arabia [64], also termed as water-entrainment aggregates, was used for the self-curing condition. Vesicular basalt aggregates were taken from dark-colored volcanic basalt rock characterized by pores, as shown in Figure 1. Vesicular basalt is fine to medium grained, made up of 60% plagioclase (labradorite), 35% pyroxene (augite) and 5% iron oxides and clay minerals. Vesicular basalt rock has non-connected pore spaces ranging in diameter from a fraction of a millimeter to a few centimeters, with a nominal diameter of 8 mm. The pore space distribution also ranges from being sporadically to densely distributed; pores vary in shape between being spherical and irregular, but are generally spherical.

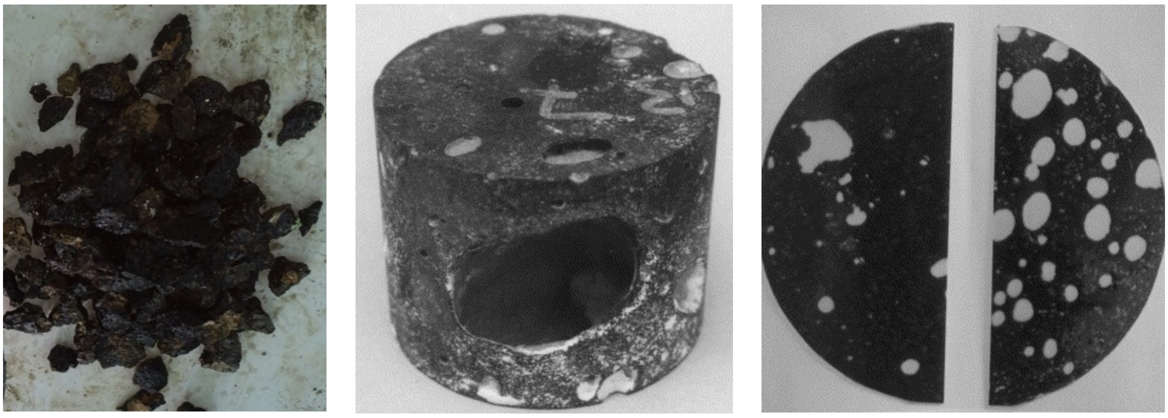


Figure 1. Vesicular basalt aggregates and parent material (water-entrainment aggregates) [64].

The size of porous vesicular basalt aggregates, replaced as coarse aggregate, was varied, ranging from 20 to 40 mm. Water absorption, after 24 h water immersion in the self-curing agents, porous aggregates of vesicular basalt, was found to be 5%. Water absorption in the normal aggregate was determined at 1.1%.

2.1.3. Curing Compound for Membrane Curing

Concure WB, manufactured by Fosroc International Limited, is a water-based concrete curing compound based on a low viscosity wax emulsion and having specific gravity of 1–1.01. It comes as a white emulsion, creating a transparent drying film. When applied to a fresh concrete surface, the emulsion splits into a continuous, non-penetrating coating. Concure WB, compliant with ASTM C309 [65], with dosage of 3.75 m^2/L, was used for the membrane curing of concrete having a water–cement ratio of 0.5.

2.1.4. Concrete Composition and Concrete Workability

The mix proportions for concrete used are shown in Table 5.

The fresh concrete workability was quantified in terms of the slump value by conducting the slump test as per ASTM C143 [66]. The workability of the concrete mix having water–cement ratio of 0.5 in terms of slump was measured at 50 mm. For a water–cement ratio of 0.35, the workability was increased by adding the super-plasticizer. Mix workability in terms of slump was found at 40 mm.

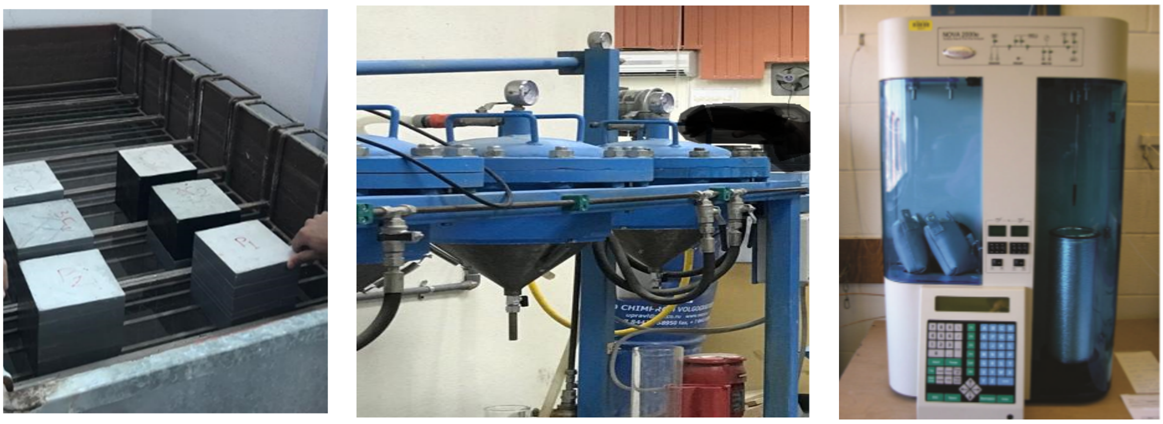
2.2. Test Set-Ups

2.2.1. Concrete Compressive Strength

The compression test on cube and cylindrical specimens was conducted on the 1000 kN universal testing machine [67,68]. The cube and cylindrical compressive strengths are estimated as crushing load per unit area. The specimens were cured under various curing conditions for 3, 7 and 28 days before testing. Specimens with the self-curing agent were also subjected to water curing for the initial three days to study the performance of initial curing conditions. Three samples were tested and mean values were noted.

2.2.2. Concrete Durability Properties

The durability conditions of concrete depend on the porosity and permeability of concrete. The water sorptivity test, the water permeability test and the BET surface area test were conducted to explore the porosity, permeability and pore-size of the hardened concrete. The test set-ups for the water sorptivity test, the water permeability test and the BET test are shown in Figure 2.



(**a**) Water sorptivity (**b**) Water permeability (**c**) BET

Figure 2. Tests set-up for durability.

Water Sorptivity (Permeability under Capillary Action) Test

Sorptivity is termed as the rate by which a wetting front moves through a porous material. Water sorptivity testing includes unidirectional water absorption into one face of a preconditioned concrete sample. In this test, an oven-dried sample was suspended above water. The sample was weighed to calculate the mass of water absorbed at predetermined intervals and sorptivity was estimated from the plot of mass of water absorbed vs. the square root of time. The lower the sorptivity index for water, the greater the potential concrete durability. Sorptivity values generally range from approx. 0.5–0.1 mm/$\sqrt{}$min, for well-cured concrete with a strength of 30–50 MPa, to 1.5–2 mm/$\sqrt{}$min for poorly cured concrete with a concrete strength of 20 MPa. The sorptivity coefficient (S) is calculated using the following formula:

$$Q/A = I = S\sqrt{t} + \text{constant or } S = [(Q - \text{Initial rate of absorption})/A]/\sqrt{t} \quad (1)$$

where S is the sorptivity coefficient (mm/$\sqrt{}$min), Q is the volume of water absorbed in mm^3, A is the surface area in contact with water in mm^2 and t is the time, in minutes, for the absorption of water in concrete.

The water absorption (sorptivity) test was performed as per ASTM C 1585 [69] to determine the sorptivity coefficient of the concrete specimens that were kept in the oven for 24 h at 105 °C and then cooled down to get a constant moisture level. Thereafter, 4 sides of the concrete samples were air tightened with cello tape or a barrier to stop the evaporation effect, in addition to maintaining uniaxial water flow during the test and leaving the opposite faces exposed. Prior to locating the concrete samples on water, their initial weights were noted down. One side of the specimen was exposed to water, whereas water absorption was noted at predefined intervals by weight. The specimens were submerged by 5 mm in water. The cycle was repeated, consecutively, at time intervals of 15 min, 30 min, 1 h, 2 h, 4 h, 6 h, 24 h, 48 h and 72 h. The set-up for the sorptivity test is demonstrated in Figure 2. The weight gain by capillary action when a standard concrete cube was immersed by 5 mm in water at various time intervals were calculated for the control concrete and the self-curing concrete (3 specimens for control concrete and for self-curing concrete, with 3/28 days water curing) to find the amount of water absorbed by the specimens during the selected time interval. "The absorption of water, I, is the change in mass (g) divided by the cross-sectional area of the test specimen (mm^2)". The water sorptivity (mm/$\sqrt{}$minute) is termed as the slope of the line of I plotted with respect to the square root of time ($\sqrt{}$minute). The slope of I vs. the square root of time is obtained using least squares linear regression to the plot of I with respect to $\sqrt{}$time.

Table 5. Mix proportions of concrete.

Mix Name	Cement Content (Kg/m^3)	Sand (Kg/m^3)	Basalt (Kg/m^3)	Silica Fume (%)	Super Plasticizer (%)	Vesicular Basalt (%)	Curing Compound [70]	Water–Cement Ratio
Mix 1	504	755	1260	-	-	-	-	0.50
Mix 2	445	755	1260	12	0.5	0	-	0.35
Mix 3	504	755	1260	-	-	-	Concure WB	0.5
Mix 4	504	755	1260	0	0	10	-	0.50
Mix 5	445	755	1260	12	0.5	10	-	0.35

Water Permeability under Pressure Test

In the water permeability test [70], a sealed pressure chamber was attached to the concrete surface. Then, water was filled into the pressure chamber and a specified water pressure was applied to the surface. The oven-dried specimens, coated with epoxy on the circular side to prevent water penetration from the side during the test, were used in the pressure chambers. The water pressure was applied to the specimens for 72 h to allow sufficient water to permeate inside the test specimens.

For the water permeability under pressure test, cylindrical specimens were dried in the oven at 105 °C for 24 h and then cooled down. The specimens were then coated with epoxy on the curved side to prevent water penetration from the curved side during the test. Before keeping the specimens in test set-up, their initial weights were recorded. A pressure of 3 bar was applied to the specimens and the pressure was maintained for 72 h in a test chamber; thereafter the specimens were split open to ascertain the water penetration depth. The specimens were weighed to ascertain the volume of water permeated.

Brunauer–Emmett–Teller (BET) Surface Area and Pore Size Test

The Brunauer–Emmett–Teller (BET) test method is employed for the estimation of surface areas of solids by physical adsorption of gas molecules. The process employs the BET theory [71] on multilayer adsorption systems and typically uses probing gasses, which do not react chemically with material surfaces as adsorbents, to quantify specific surface areas. Nitrogen is the gaseous adsorbate used often by BET methods for surface probing. With this purpose, standard BET analyses are usually carried out at N_2 boiling temperature.

The BET test method was used to assess the durability condition based on pore characteristics of the concrete matrix; the test was conducted in compliance with ASTM C1274 [72]. The size of pore distribution, including pore volume and pore size, for samples of the control concrete and self-curing concrete, were calculated from the desorption isotherm according to the Barrett, Joyner and Halenda (BJH) procedure [73].

3. Results and Discussion

3.1. Concrete Mechanical Properties

The effectiveness of water-entrainment aggregates in concrete as a self-curing agent is here investigated and compared with other types of concrete curing conditions. The compressive strength tests were conducted for specimens with different water–cement ratios and concrete surface area–volume ratios under water curing condition (control concrete), air curing condition, self-curing condition, using water-entrainment aggregates (vesicular basalt), and membrane curing conditions, using the Concure WB water-based curing compound. The experimental results, in terms of compressive strength of concrete of casted cubical and cylindrical specimens, having various water–cement ratios with normal aggregates and water-entrainment aggregates, under different curing environments, are depicted in Figures 3–5. The details of the experimental results in a tabular format have been given in the Supplementary Materials (Tables S1–S6). Figures 3 and 4 depict the cubical (concrete surface/concrete volume ratio = 40) and cylindrical (concrete surface/concrete volume ratio = 26.4) compressive strengths of concrete with a w/c (water–cement ratio) of 0.5 and vesicular basalt aggregates, under water, air, membrane and self-curing conditions at 3, 7 and 28 days, respectively. The concrete cubical compressive strengths with a water–cement ratio of 0.35 under water and self-curing condition at 3, 7 and 28 days are represented in Figure 5. The relative strength, with respect to control concrete, and the rate of development of concrete strength, with different water–cement ratio, concrete surface/concrete volume ratio and different water-entrainment aggregates at different age and curing conditions, are shown in Figures 6–8.

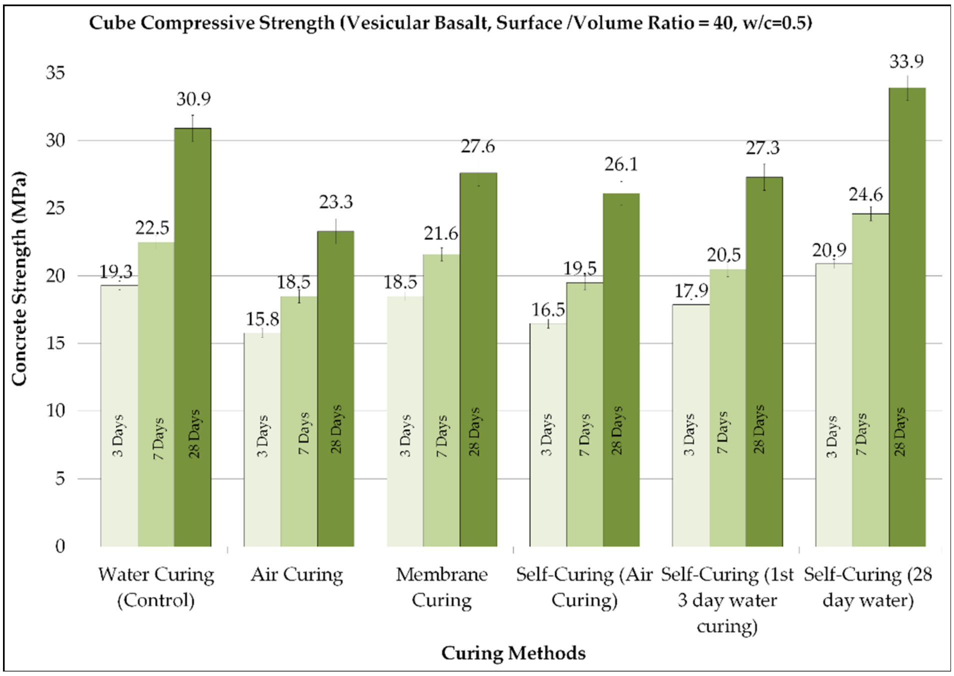


Figure 3. Concrete strength (MPa) under different curing condition and curing age, using vesicular basalt aggregates (concrete surface–volume ratio = 40, water–cement ratio = 0.5).

From Figures 6–8, it is noted that concrete compressive strength increases with the increase of the curing duration. However, the increase in strength varied with duration and curing condition. The highest compressive strength was obtained with combination of self-curing and external curing, while the least compressive strength was developed with no curing, as expected from the cement hydration characteristics under such curing conditions. It is also evident that water curing was more efficient than membrane curing of concrete. The water-cured specimens had 10% more strength than the membrane-cured concrete specimens. Compared to concrete under air curing, concrete strength was greater in concrete under self-curing and strength further increased with the first three days of water curing. It can be inferred that self-curing recovers the loss of concrete strength due to partial water curing of concrete. Figures 6–8 show the development of compressive strength of self-curing concrete in comparison to control concrete (water curing condition) with different water–cement (w/c) ratios and surface area/volume (S/V) ratios. The figures show that the water–cement ratio and surface area/volume ratio of concrete affect considerably the mechanical properties of concrete cured under different conditions. The self-curing approach is more effective for concrete having lower water–cement ratio and lower surface area/volume ratio. It was also found, from the figures depicting the rate of progress of compressive strength in concrete, that the curing procedure affected the compressive strength of concrete more during the latter ages, as compared to the initial ages, and that the self-curing improved the rate of development of concrete strength at various curing durations. Additionally, the rate of strength development of concrete was higher during the latter ages, with a w/c ratio of 0.5. While for a w/c ratio of 0.35, higher strength development was observed at an early age. However, water curing during early ages, in addition to self-curing, also improved the strength development at latter ages. The self-curing conditions enhance the cement hydration process and the self-curing agent is a useful concrete admixture for development of high-performance sustainable concrete.

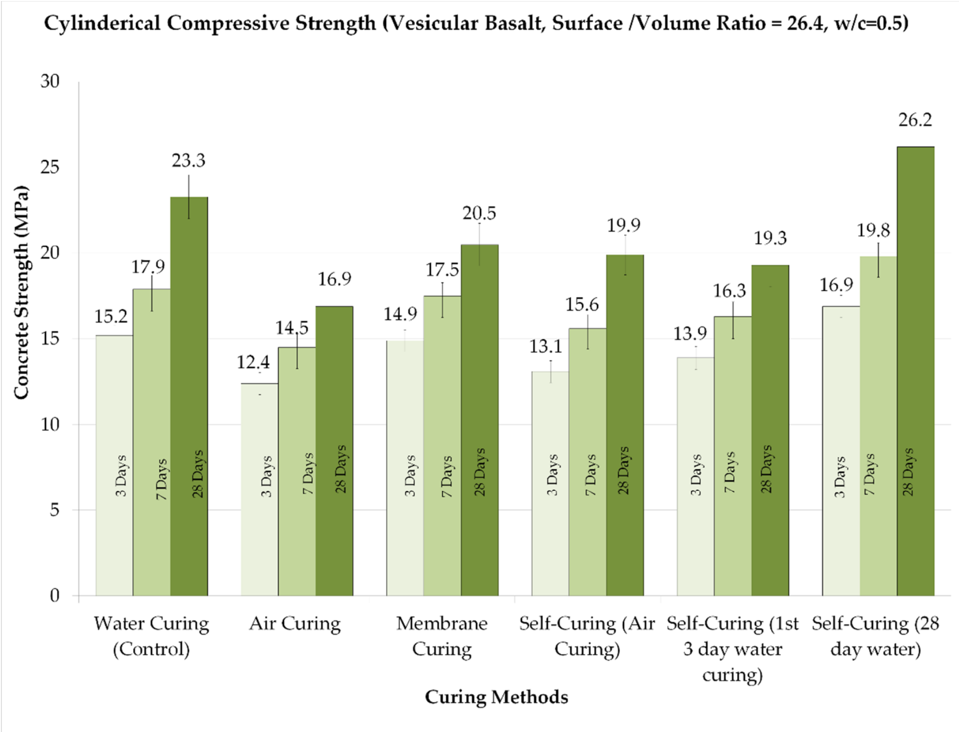


Figure 4. Concrete strength (MPa) under different curing condition and curing age using vesicular basalt aggregates (concrete surface–volume ratio = 26.4, water–cement ratio = 0.5).

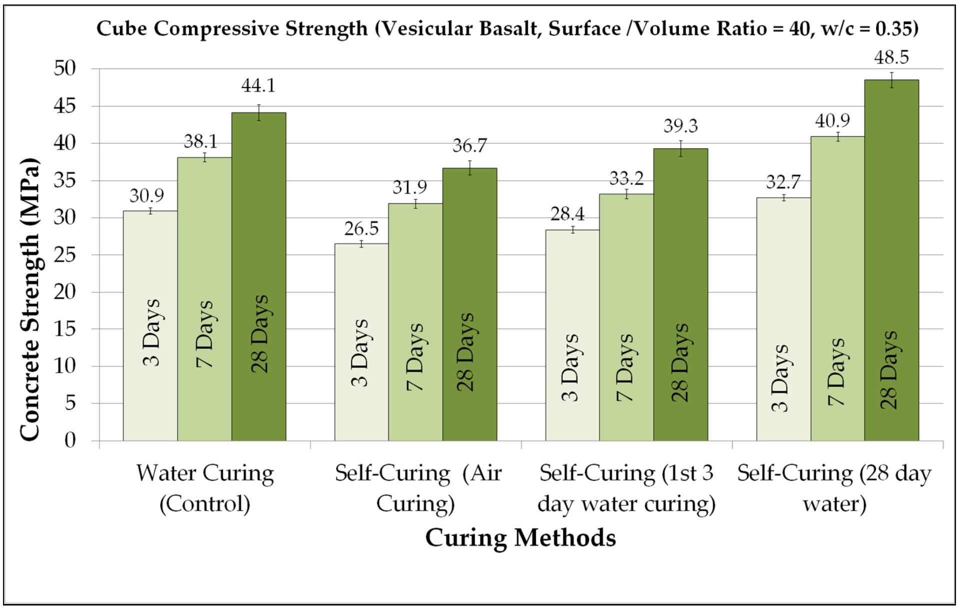
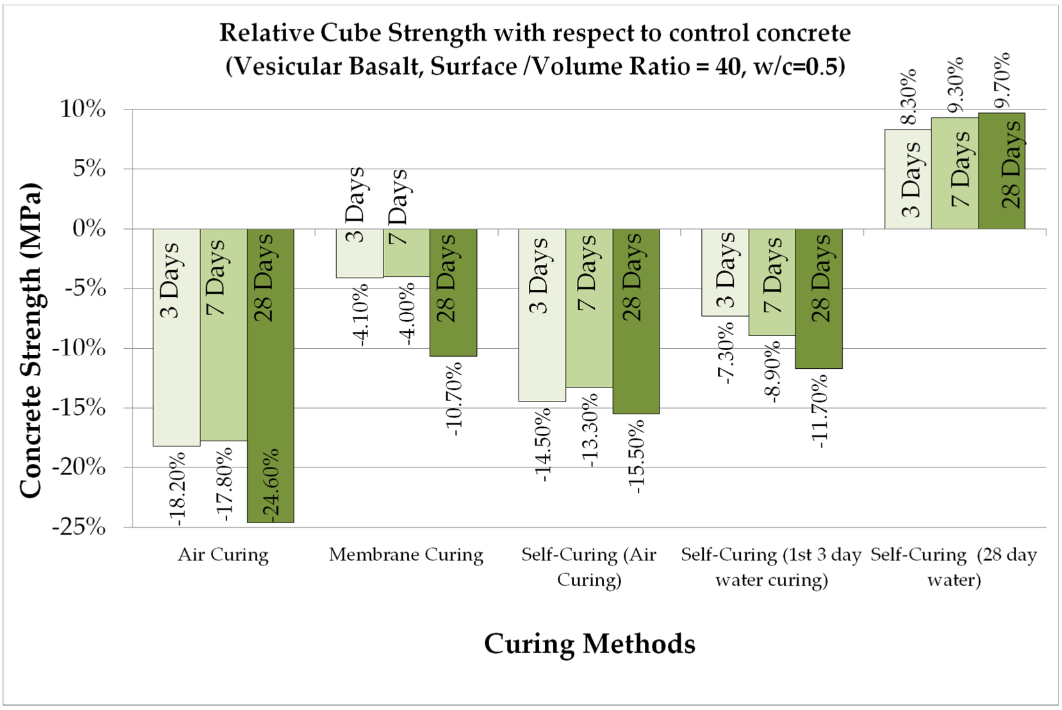
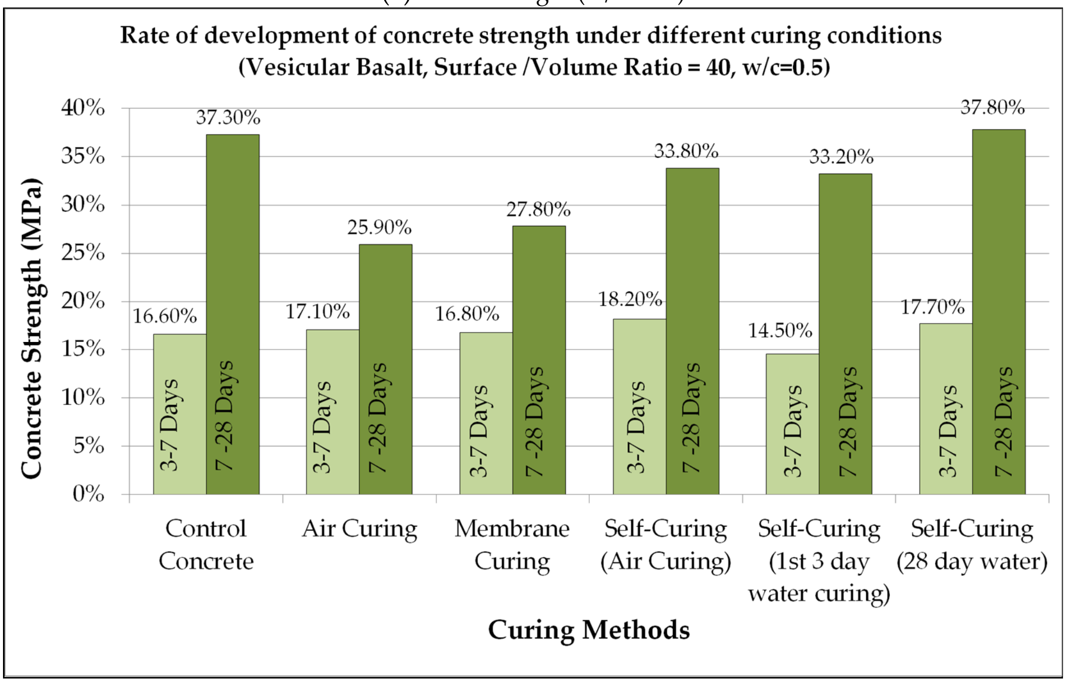


Figure 5. Concrete strength (MPa) under different curing condition and curing age using vesicular basalt aggregates (concrete surface-volume ratio = 40, water–cement ratio = 0.35).

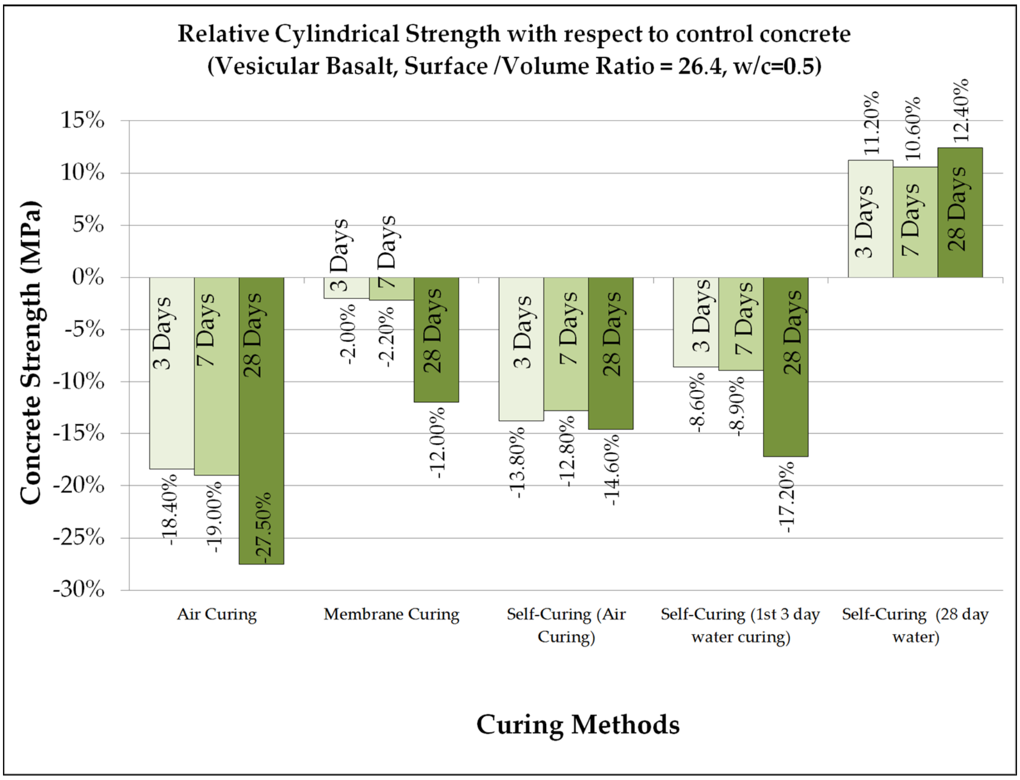


(**a**) Cube strength (w/c = 0.5)

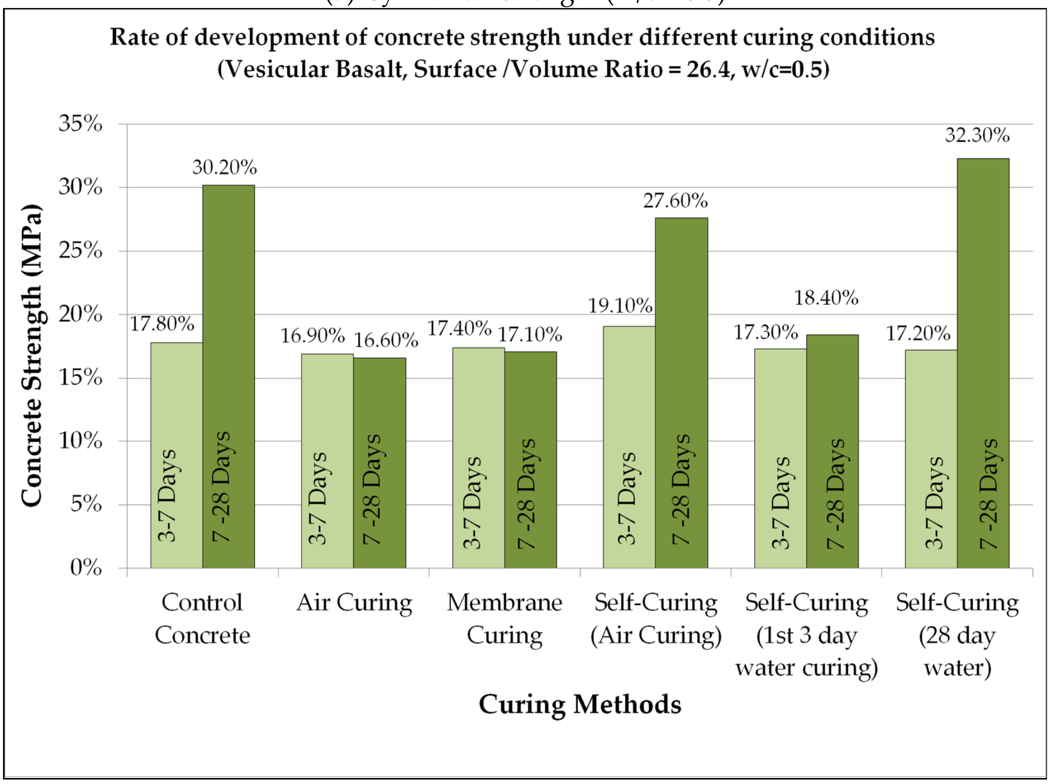


(**b**) Rate of development of cube concrete strength (w/c = 0.5)

Figure 6. Relative cube strength (surface/volume ratio = 40, w/c = 0.5, vesicular basalt), with respect to control concrete, and rate of development of concrete strength under various curing environment.

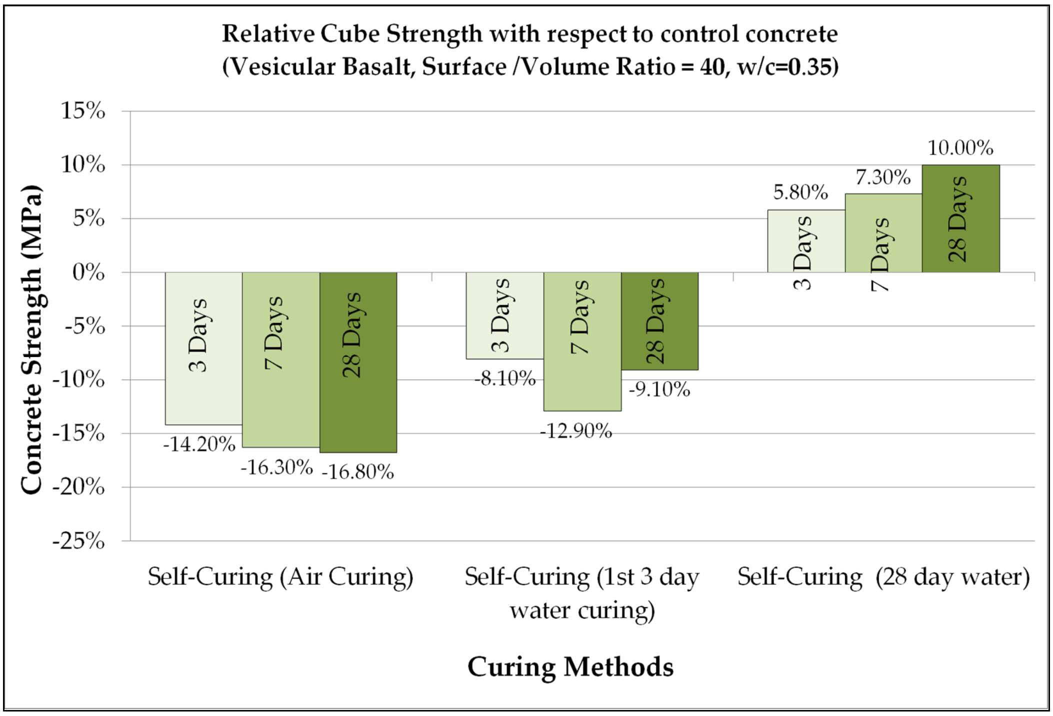


(**a**) Cylindrical strength (w/c = 0.5)

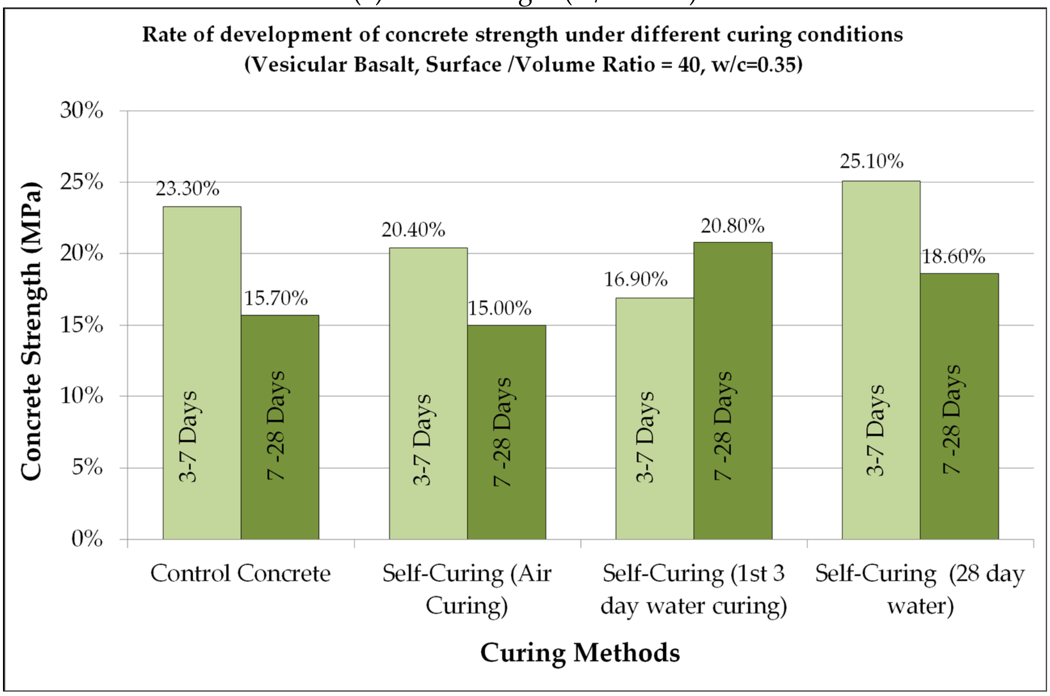


(**b**) Rate of development of cylindrical concrete strength (w/c = 0.5)

Figure 7. Relative cylindrical strength (surface /volume ratio = 26.4, w/c = 0.5, vesicular basalt), with respect to control concrete, and rate of development of concrete strength under different curing conditions.



(**a**) Cube strength (w/c = 0.35)



(**b**) Rate of development of cube concrete strength (w/c = 0.35)

Figure 8. Relative cubical strength of self-curing concrete having low water–cement ratio (surface/volume ratio = 40, w/c = 0.35), with respect to control concrete, and rate of concrete strength development.

3.2. Concrete Durability Properties

The porosity, permeability and pore size of the hardened concrete, the durability indicators, were found from the water sorptivity (water permeability under capillary action) test, the water permeability under pressure action test and the Brunauer–Emmett–Teller (BET) surface area test. The graph of absorption of water (I), with respect to square root of time for water sorptivity for conventional curing concrete (control concrete) and self-curing concrete, is shown in Figure 9. The water sorptivity obtained from Figure 9 for the control and self-curing concrete, as per the equation given above for sorptivity, is shown in Table 5. The obtained sorptivity coefficient values, representing the porosity of concrete, show that the sorptivity coefficient is lesser for self-curing concrete and the sorptivity coefficient for the control concrete is almost the same as the sorptivity coefficient for the self-curing concrete, with only the initial three days of water curing. Similar results for sorptivity with addition of curing agent in concrete were obtained by Grabiec et al. [38].

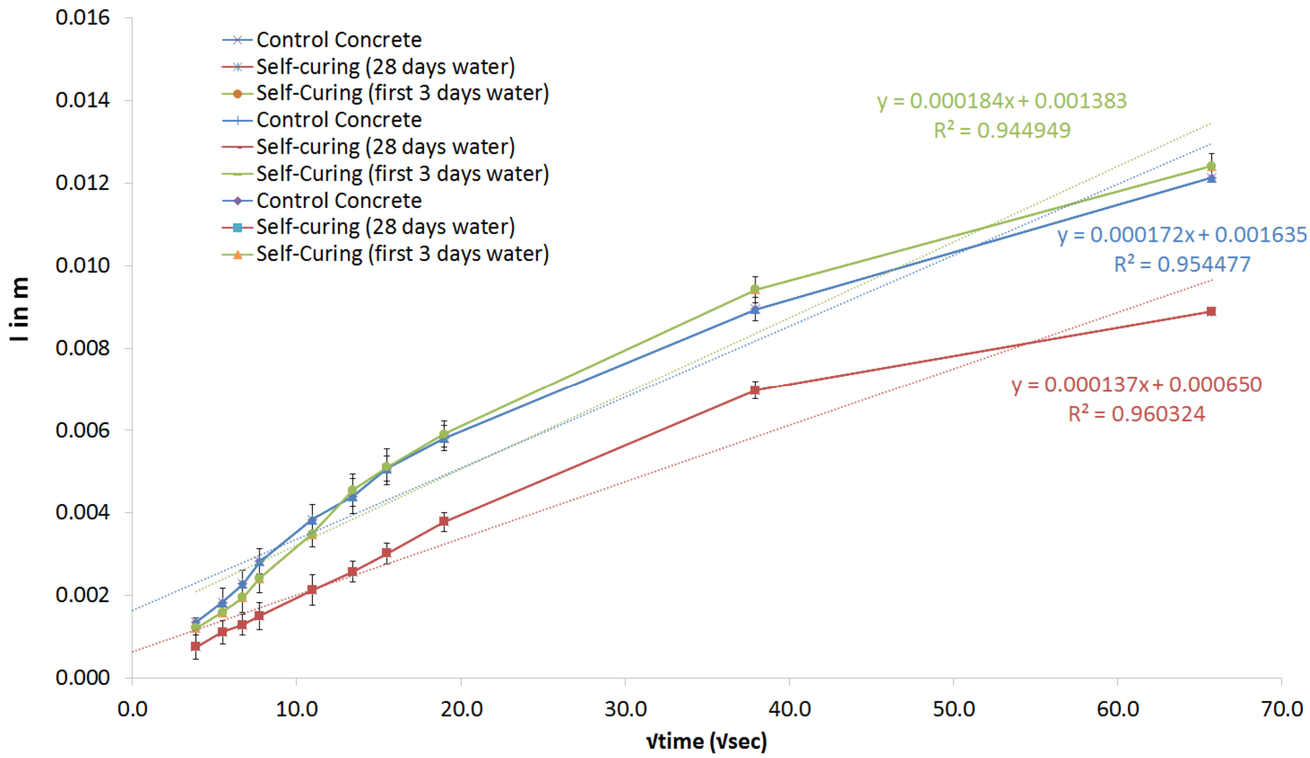


Figure 9. Absorption of water vs. square root of time graph for water sorptivity for control concrete and self-curing concrete.

The results of weight gain by forced pressure action for 72 h in a standard water permeability test apparatus for control concrete and self-curing concrete with 3/28 days water curing are given in Table 6. The under-pressure water permeability is lesser for self-curing concrete and the water permeability of the control concrete is greater than the water permeability of the self-curing concrete, with only the initial three days of water curing. The results indicate that the addition of a self-curing agent reduces the porosity and pores continuity of the concrete matrix and helps to enhance the durability properties of concrete.

Table 6. Sorptivity coefficient and volume of permeated water from water permeability tests.

Concrete Type/ Curing Method	Sorptivity Coefficient (S, $m/\sqrt{sec^1}$)	Volume of Permeated Water [cm^3]
Control concrete (28-day water curing)	0.1725	85.6
Self-curing concrete (only 1st 3-day water curing)	0.1839	86.1
Self-curing concrete (28-day water curing)	0.1371	83.7

The pore size distributions, including pore size and pore volume, for samples of control concrete and self-curing concrete obtained from the BET test are given in Table 7.

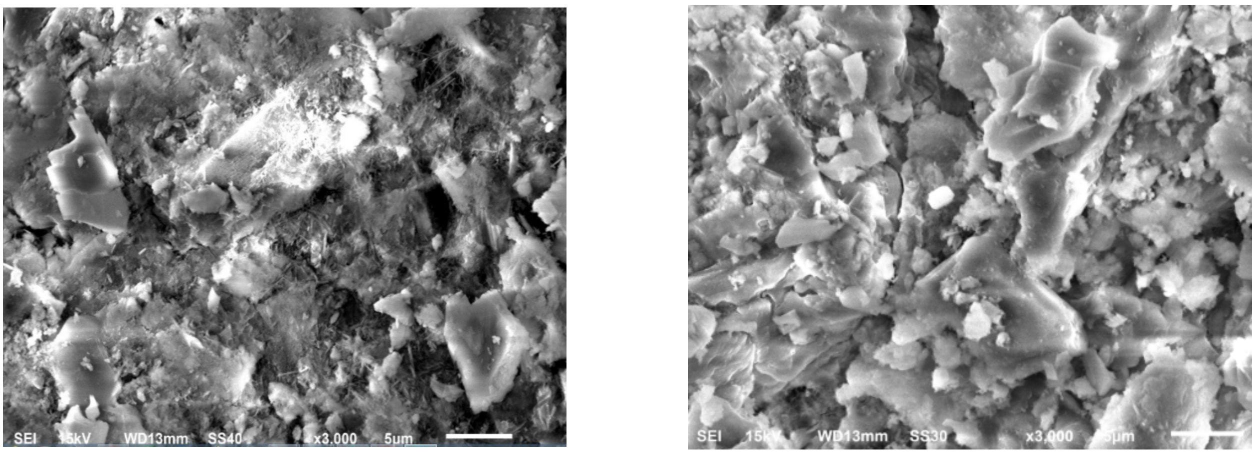
A comparison of the specific surface area and pore volume of the control concrete and self-curing concrete specimens tested showed that the self-curing concrete exhibited a higher specific surface area and pore volume. This indicates that the material pore structure becomes finer with self-curing and is reflected in the reduced pore size of the self-curing concrete in comparison to the conventional curing concrete. It is inferred that the incorporation of water-entrainment aggregates enhances the durability properties of the concrete.

Table 7. BET test results for surface area, pore size and pore volume.

Concrete Type/Curing Method	Area of Surface [m^2/g]	Volume of Pore [cm^3/g]	Size of Pore [A]
Water curing (control concrete)	4.768	1.068×10^{-2}	23.94
Self-curing concrete (28-day water curing)	5.131	1.286	23.87

3.3. Micro-Structure Characterization

The improvements in the micro-structure of concrete improve the strength and durability properties of concrete. The SEM micro-structure images of the control concrete, or water-curing concrete, and self-curing concrete (28-days water curing), with a 0.5 w/c ratio, are given in Figure 10. The figures depict that the addition of water-entrainment aggregates to concrete for self-curing results in the filling of micro-pores, or pore size reduction, in the hydration product matrix. For the self-curing concrete, more uniform hydration products were observed as compared to the water-curing concrete, because of continuous availability of water during the cement hydration process. Similar improvements in micro-structure due to the addition of a self-curing agent were observed by Khotbehsara, et al. [37].



(**a**) Water cured concrete (**b**) Self-cured concrete (28 days water curing with 0.5 w/c ratio)

Figure 10. Microstructure of control concrete and self-curing concrete (SEM images).

3.4. Present Study Limitations and Recommendations for Future Work

The present study has the limitation that it is very difficult to distribute the water-entrainment aggregates uniformly; an arbitrary quantity of curing agent was selected, as the guidelines are not available to decide the optimum dose of the curing agent (normal weight porous aggregate). The results on concrete durability properties, in the present study, have the limitation that the results are based on an arbitrary mix proportion with used cement content and workability. Further studies are clearly needed to develop a concrete mix design method for sustainable self-cured concrete having the optimum dose of water-entrainment aggregates and cement content with good workability. Further work on self-curing concrete could be carried out with other durability indicator tests, such as the chloride penetration test, various shrinkage tests, etc. A study could be conducted to compare the durability tests results of the sample taken from a different location of the concrete specimens containing various quantities of the curing agents and to study the size of the influence zone of water-entrainment aggregates. Future studies on self-curing concrete could include longer initial water curing (i.e., 4, 7 days) and investigations on concrete could be at greater ages (i.e., 56, 90 days). The performance of the self-curing method could be studied in nanoparticles-modified concrete.

4. Conclusions

Sustainable concrete was developed, in this work, through sustainable concrete production processes, i.e., self-curing, or internal curing method, and sustainable concrete ingredient materials, i.e., locally available water-entrainment aggregates of vesicular basalt. The quantitative evaluation of the environmental and socio-economic sustainability indicators, i.e., strength and durability of the self-cured concrete, were carried out and the effectiveness of the self-curing method, using the water-entrainment aggregates, on the durability and mechanical characteristics of concrete, were investigated. The porosity, permeability and pore size of the hardened concrete, the durability indicators, were found via the water sorptivity (water permeability under capillary action) test, the water permeability under pressure action test and the Brunauer–Emmett–Teller (BET) surface area test. The following conclusions may be drawn from the present study.

1. Concrete strength and rate of strength development of the self-cured concrete were enhanced due to improvement in the cement hydration process. This may be attributed to variable loss of water or water availability under self-curing condition. The self-curing method provides better performance of concrete having lower water–cement ratio and lower concrete surface-volume ratio. An increase of up to 10 % in compressive strength of self-cured concrete was observed over the conventionally cured concrete.
2. More uniform hydration products were observed in self-curing concrete, as compared to water curing concrete, because of continuous availability of water during the cement hydration process by the addition of water-entrainment aggregates.
3. The addition of water-entrainment aggregates results in a finer pore structure of concrete. The size of pores was reduced from 23.94 A^0, in conventionally cured concrete, to 23.87 A^0, in self-cured concrete. An increase of 10% in the solid surface area of the self-cured concrete was observed over the conventionally cured concrete.
4. The addition of water-entrainment aggregates in the concrete improves the water transport mechanism. The sorptivity coefficient of concrete was increased by the addition of water-entrainment aggregates.
5. The self-cured concrete, having locally available water-entrainment aggregates of vesicular basalt and higher strength and durability, satisfies the socio-economic and environmental aspects of sustainability, as it results in proper resource utilization, improvement of quality of life (long life, lower CO_2 emission and material wastage), reduction in costs (less water usage and maintenance) and increased economic activity in society for concrete production.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13126756/s1, Tables S1–S6.

Author Contributions: Conceptualization, M.A. and S.A. (Saleh Alsulamy); data curation, M.A., R.A.K. and M.D.; formal analysis, M.A., S.A. (Saeed AlQadhi) and S.I.; funding acquisition, M.A.; methodology, M.A., S.A. (Saeed AlQadhi), S.A. (Saleh Alsulamy), R.A.K. and M.D.; project administration, M.A.; resources, S.A. (Saeed AlQadhi), S.A. (Saleh Alsulamy) and S.I.; supervision, S.A. (Saleh Alsulamy); writing—original draft, M.A., S.A. (Saeed AlQadhi) and S.I.; writing—review and editing, S.A. (Saeed AlQadhi) and S.A. (Saleh Alsulamy). All authors have read and agreed to the published version of the manuscript.

Funding: The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through the General Research Project under grant number [R.G.P2 /73/41].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors acknowledge the Dean, Faculty of Engineering, for his valuable support and help.

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

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