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CO_2 concrete and its practical value utilising living lab methodologies

Vivian WY. Tam [a,*], Anthony Butera [a], Khoa N. Le [b], Wengui Li [c]

[a] School of Built Environment, Western Sydney University, Penrith, NSW, 2751, Australia
[b] School of Engineering, Western Sydney University, Penrith, NSW, 2751, Australia
[c] School of Civil & Environmental Engineering, University of Technology Sydney, Sydney, NSW, 2007, Australia

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ABSTRACT

The sequestration of carbon dioxide into recycled aggregates for the enhancement of recycled aggregate concrete has provided an abundance of potential over recent years. The injection of carbon dioxide creates a strong concrete, known as CO_2 Concrete, which can rival virgin aggregate concrete in overall performance. However, previous research only delves into small-scale testing. This paper demonstrates the potential for CO_2 Concrete to be used in large-scale practical applications through living lab methodology. The compressive strength of CO_2 Concrete offers great potential. After the carbon-conditioning of aggregate, the recycled aggregate concrete achieved the 95.1% strength when compared to the virgin aggregate concrete. Furthermore, it greatly surpassed the untreated recycled aggregate concrete which only exhibited a compressive strength of 64.76% when compared to the virgin aggregate concrete. This trend is also demonstrated by the two living lab projects. The living labs project consisted of two biosecurity platforms with a size of 780 mm long, 560 mm wide and 120 mm deep as well as four cattle drinking station slabs with a size of 3 m in length, 2.6 m in width and 0.2 m in thickness for agricultural use for Hawkesbury Campus, Western Sydney University. The biosecurity platforms are used for the cleaning of boots between paddocks in order to prevent the spread of disease whilst the slabs are utilised for the support of cattle drinking basins and to retain a desirable ground level, which would normally be eroded by cattle. The living labs achieved an outstanding 28-day compressive strength even surpassing virgin aggregate concrete on some occasions. The labs also demonstrated great durability. The employment of non-destructive testing shows the CO_2 Concrete can preserve compressive strength under harsh agriculture conditions, which can include chemical attack, cattle movement and heavy machinery loading. After over a year and a half of practical application, the biosecurity platforms have not experienced depreciation according to the non-destructive testing. Visual inspections also reveal minimal degradation with only the sharp edges of the biosecurity platforms rounding over after a year and a half. The overall performance of CO_2 Concrete is outstanding and has the potential to replace the typical virgin aggregate concrete.

1. Introduction

The injection of carbon dioxide (CO_2) into recycled aggregate as well as cement pastes has demonstrated great potential, delivering enhanced mechanical properties to an overall concrete. The mechanism by which CO_2 transforms the larger calcium hydroxide into smaller calcium carbonate permits the filling of air voids providing the densification of a cement paste which mitigates negative properties (Li et al., 2018) (Zhang et al., 2017). The accelerated injection of CO_2 mirrors that of the natural mechanism of carbonation, which can take years or even decades to achieve a required depth of penetration. The injection of pure CO_2 at pressure under the correct humidity and environment hastens the chemical reaction and realises an enhanced cement paste (Monkman et al., 2016) (Xuan et al., 2016b). The injection of CO_2 into cement can be split into two broad categories. First, the sequestration into the cement paste of concrete after casting, and secondly, into the recycled aggregate itself. The injection of CO_2 into concrete blocks is referred to as carbon curing, whereas the introduction of the gas into recycled aggregate is known as carbon-conditioning. The aforementioned processes for the accelerated carbonation of cement provides an abundance of promise, however, have not yet been tested in the field at a large scale.

Carbon curing can deliver an average of 15%–20% improvement to compressive strength at 28 days, depending upon the carbonation variables such as duration, pressure humidity, moisture content of

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* Corresponding author.
E-mail address: vivianwytam@gmail.com (V.WY. Tam).

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aggregate and concentration of CO_2 (Zhan et al., 2016) (Monkman and Macdonald, 2016). A number of past researchers have revealed this strength trend in both recycled aggregate concrete and virgin aggregate concrete, whilst other researchers have investigated the carbonation reaction of cements in great details, which have underpinned the concrete research (Ahmad et al., 2017) (Moon and Choi, 2019b). The enhancement of cement paste by the CO_2 gas is quite clearly established by carbon curing, however, the supplementary strengthening technique does possess some negative attributes in terms of practical application of the procedure.

The impracticality of carbonating concrete after casting is that there is a requirement to inject gas into large blocks; this cannot be achieved in-situ and requires the concrete to be largely of a precast variety. Secondly, the infiltration of CO_2 into cement becomes difficult as the outer layer of the concrete is carbonated because it has become denser, as a result of which, the path to the centre of the concrete is obstructed (Zhan et al., 2014) (Zhan et al., 2018). Furthermore, the greater the surface area of the material for carbonation, the quicker the material be carbonated; the surface area to volume ratio is higher in the case of carbonation of recycled aggregate, or carbon-conditioning (Tam et al., 2016) (Haselbach and Thomle, 2014).

The conversion of calcium hydroxide ($Ca(OH)_2$) to calcium carbonates ($CaCO_3$) produces cement with a lower pH (under 9), which can initiate corrosion of the reinforcement bars (Zhang et al., 2017) (Xuan et al., 2018). In order to reap the benefits of the mechanical quality resulting from the injection of CO_2 into cement, this issue must be circumnavigated. In the case of carbon curing, it is difficult to address this issue as the entire cement paste is to be carbonated, which results in contact with the reinforcement bars. In the case of carbon-conditioning, only the aggregate is to be carbonated, which lowers the pH of the attached cement paste; however, it is difficult for the aggregate to come into contact with the reinforcement bars as they are both typically coated with cement. Past research indicates that the incorporation of carbonated recycled aggregate is better for the steel reinforcement over untreated recycled aggregate (Zhan et al., 2019). Additionally, the pH of the virgin aggregate rock can also be considered to be close to that of carbonated recycled aggregate (Neville, 2012) (Mehta, 1986).

The objective of the carbonation of recycled aggregate is to convert calcium hydroxide found in the residual attached cement into calcium carbonate. The conversion to calcium carbonate fills voids with the attached cement, strengthening the weakest section of the recycled aggregate itself. Carbon-conditioning can offer similar results, with typical improvements of 15%–20% to compressive strength at 28 days depending on carbonation duration, carbonation pressure, humidity, moisture content of aggregate and concentration of CO_2 (Wu et al., 2018) (Kou et al., 2014b). The 100% carbon-conditioned recycled aggregate concrete can deliver an improvement of 10% below that of virgin aggregate concrete in compressive strength. Even though the effects of the carbonation of recycled aggregate have been investigated, a greater number of studies have focussed on improving the recycled aggregate itself rather than the concrete mixed with the enhanced recycled aggregate. Investigators have collaborated to research aspects, such as the mechanical properties of carbonated recycled aggregate concrete, the improvements in density, water absorption, crushing value, as well as microstructural analysis, all of which improve (Kou et al., 2014a) (Xuan et al., 2016a) (Zhan et al., 2014).

The injection of CO_2 into recycled aggregate allows for a quicker carbonation time, as aggregate is smaller than concrete blocks and exhibit a larger surface area to volume ration. Furthermore, the new cement binder is not made more acidic meaning the carbon-conditioned recycled aggregate concrete will avoid the corrosion of reinforcement bars. However, the use of recycled aggregate does offer some issues. Depending on the location of acquisition, recycled aggregate quality can vary based upon a recycling plants ability to adequately separate poor materials such as organics. The variance in quality can only be counteracted by the selection of appropriate material. Furthermore, recycled concrete aggregate has the potential to have other supplementary materials, most commonly fly ash and slag. Whilst these cementitious materials have the potential to consume additional or all calcium hydroxide from ordinary cement, they also contain compounds such as magnesium oxide and calcium oxide that ultimately produce calcium carbonate upon carbonation. Whilst different cements can have different carbonation rates, cementitious materials typically contain compounds that cause densification when carbonated (Monkman and Shao, 2006) (Moon and Choi, 2019a).

The accelerated sequestration of CO_2 into recycled aggregate exhibits the highest potential for the enhancement of aggregate and concrete performance and must be studied over the next several years. In order to develop a complete understanding of the CO_2 Concrete, a greater detail of research must be attained. Currently, there is a fair understanding into the enhancement of recycled aggregate as well as concrete; however, all testing has been in a small-scale. In order to attain a greater understanding of carbon-conditioned recycled aggregate concrete the material should be used in large-scale practical applications.

Living lab projects allow for the implementation of experimental works into a practical environment. The concept allows for real-life and practical exposure from external stakeholders which can deliver extended knowledge beyond standard testing. Whilst the living lab methodology of research has not been commonly adopted within concrete, it has indicated promise in other research fields (Evans et al., 2015) (Gascó, 2017). In the case of the study of concrete the living lab style of methodology does not provide information that is delivered by standard testing which is the likely culprit for the less common use of the research method within the field. However, coupling the methodology with previous literature as well as standard testing, it can provide a further insight into large-scale concreting. Consequently, as existing literature supports the carbonation of recycled aggregate concrete on a small-scale, the living lab style of experimentation should now be taken into consideration to further study the promising material.

2. Study aim

The research objective of this paper is to confirm previous researches by utilising standard compressive tests before and after CO_2 injection but also extend into the practical use of the concrete. Large-scale CO_2 Concrete will be created for a living lab style of investigation and will assist in the furthering of knowledge for CO_2 Concrete. This has the potential to uncover any unforeseen mechanism outside of standard testing, confirm if the concrete is a practical replacement for virgin aggregate concrete and provide additional information for the durability of the sustainable material.

3. Experimental program

The examinations included in this study can be split into two main categories, mechanical testing and living labs.

3.1. Mechanical testing

Mechanical properties of concrete with carbonated recycled aggregate will be examined and compared with a standard virgin aggregate concrete. Virgin aggregate will be replaced by recycled aggregate by 100% and the strength will be measured before and after the carbon-conditioning (i.e. CO_2 injection) of recycled aggregates.

3.2. Living lab projects

Two living lab projects are created in order to investigate the practical feasibility of CO_2 Concrete. The living labs shall satisfy multiple agricultural requirements for Hawksbury Campus, Western Sydney University, Australia.

3.2.1. *Biosecurity platforms*

The smaller of the two applications requires the casting of two small concrete pads for application as a biosecurity platform. The biosecurity platforms are necessary within the campus for brushing of shoes between the various agricultural paddocks so as to not transmit diseases or any unwanted plant seeds among them. The pads are to be 780 mm long, 560 mm wide and 120 mm deep. This size allows for placement of anchors (concrete ferrules) for the attachment of shoe brushes and provide room for a person to stand whilst cleaning shoes. The anchor points (concrete ferrules) must be tied into the steel reinforcement. The reinforcement design is as prescribed by AS 3600, treating the platform as a pavement (slab on ground). AS 3600 prescribes a minimum compressive strength of 32 MPa and concrete cover of 20 mm. However, the greatest strength possible will be attempted with carbonation.

3.2.2. *Cattle drinking station slabs*

The second and the more trying of the two applications is the implementation of four large slabs as part of cattle drinking stations. The slabs must bear a dead load of 2.6 tonnes, as a drinking bath must be placed atop the slab and live loads of cattle; a single animal can weigh up to a tonne. The application of CO_2 Concrete in this environment is a test for the replacement of conventional, virgin aggregate concrete and offers an excellent practical examination of the sustainable CO_2 Concrete. In order to accommodate the requirements of functionality of the slabs, they must be 3 m in length, 2.6 m in width and 0.2 m in thickness. Design considerations including the reinforcement design is designated by AS 3600, treating the slabs as a pavement. The environment is considered A1 (good condition), the slabs having a hardcore fill, dampproof membrane. AS 3600 designates Hawkesbury, New South Wales a temperate location. This is a good location, where exposure to freeze-thaw conditions do not occur. A minimum of 32 MPa with a concrete cover with 20 mm concrete cover is prescribed. However, the highest strength possible practical strength that carbonated recycled aggregate concrete can achieve will is to be employed with a 40 mm concrete cover. The slabs have a brushed finish with bullnose (rounded over) edges.

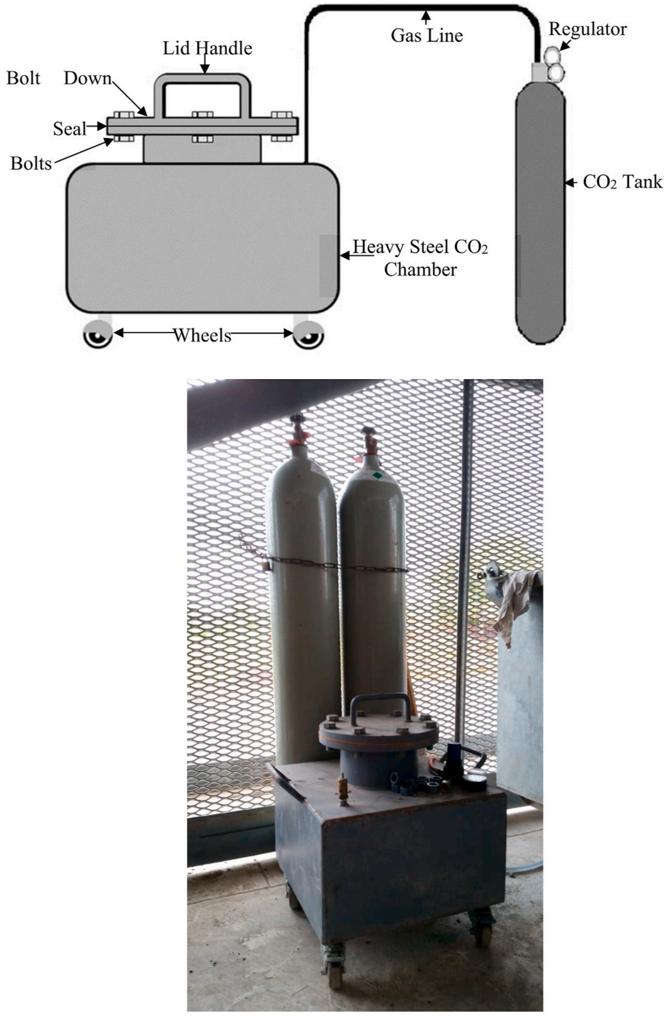

Fig. 1. Carbon-conditioning chamber.

3.3. *Carbon-conditioning chambers*

The sequestration of CO_2 into recycled aggregate is completed with the use of a steel chamber. Two chambers are employed in experimentation, a smaller chamber for modest concrete pours and a larger structure for upper scale concrete placement. The chambers allow for recycled aggregate to be exposed to pure pressurised CO_2 to accelerate carbonation.

The smaller of the two carbon-conditioning chambers utilised for the process of introducing CO_2 into recycled aggregate can be observed in Fig. 1. The smaller CO_2 chamber is a rectangular shape, sized at 500 mm by 500 mm by 300 mm. The chamber can hold a maximum aggregate weight of 50 kg whilst maintaining the ability to carbonate recycled aggregate successfully. The recycled aggregate can be introduced into the chamber by the lid which can then be fastened down using the eight bolts of the chamber. The lid and the chamber are separated by a gasket to ensure that CO_2 cannot escape from the chamber. This chamber will be employed in the creation of CO_2 concrete for small compressive cylinders and the biosecurity platforms.

The large carbon-conditioning chamber utilised in the process of introducing CO_2 into recycled aggregate can be observed in Fig. 2. The chamber a cylindrical shape with a height of 1600 mm and a diameter of 1200 mm. The larger chamber can possess up to 1 tonne of recycled aggregate. The chamber has two bolted doors, a cylindrical ingress point on the top and square exit point on the bottom. The chamber lids both contain gaskets which ensure that CO_2 is entrapped within the chamber. The chamber will carbonate the recycled aggregate for the cattle drinking station slabs.

The carbonation chambers are connected to a CO_2 cylinder with a regulator, which is used to control the CO_2 pressure although for this investigation the pressure is kept at a consistent 25 kPa. The chamber is manually vented to ensure a high concentration of CO_2, close to 100%. The aggregate placed in the chambers contain natural moisture contents. Silica gel is also placed inside the chamber so that the effect of any H_2O produced during the reaction is nullified. The process only relies on the transfer of CO_2 from bottle to chamber and requires no electricity. If the CO_2 is captured from the atmosphere by a sustainable method the entire process only sequesters CO_2 and does not produce any.

3.4. *Methods and materials*

3.4.1. *Materials*

The aggregate utilised within experimentation is pure recycled concrete aggregate in addition to virgin aggregate (basalt). A centralised recycling plant in south-eastern Australia provided the virgin aggregate utilised in experimentation whilst a southern Australian recycling plant provided the recycled concrete aggregate. The recycled concrete aggregate used in the investigation was characterised by only containing crushed concrete, excluding other recycled materials such as bricks and tiles. The cements utilised include both general purpose cement for the cattle drinking station slabs (in accordance with AS 3972) and general blended cement for the biosecurity platforms, the latter of which contains 30% fly ash and 70% general purpose cement. The use of general blend cement provides the opportunity to observe how fly ash can improve the durability and interact with carbonated recycled aggregate

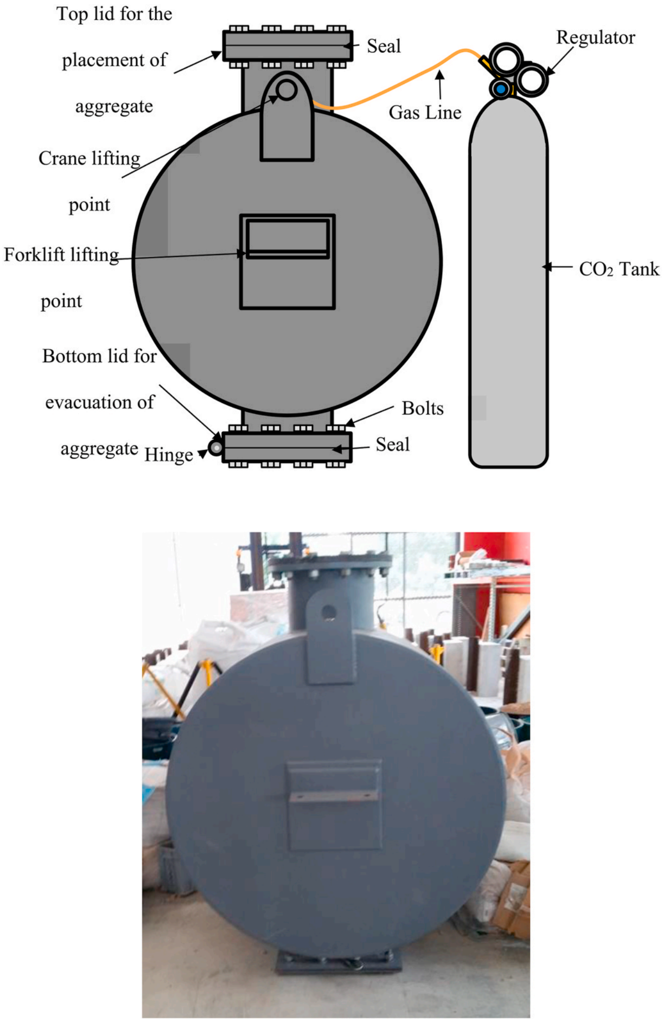

Fig. 2. Large carbon-conditioning chamber.

concrete. Sand was provided by a south-eastern Australia supplier. No admixtures are employed into concrete mixing with exception to the biosecurity platforms which will contain plasticiser, MasterPolyheed 8190, as well as air entraining agent, MasterSuna 5060. The admixtures are mixed in accordance with the BASF manufacturing guidelines of 300 mL of admixture for 100 kg/m^3 of cement. The addition of water reducing admixture allows for another durability variable to be observed in conjunction with carbonated recycled aggregate concrete.

Fig. 3 demonstrates the particle size distribution of the materials in accordance with AS 1141.11. Two different graded aggregates sizes are to be used, 10 mm and 20 mm. These graded sizes have a max diameter of 10 mm and 20 mm but have a blend of all sizes below the maximum size. The two sizes allow for a strong, workable and durable concrete mixture. Table 1 displays the properties of virgin aggregate as well as recycled concrete aggregate before and after carbon-conditioning.

Table 1 show that the carbonation of recycled aggregate for 1 h with a 25 kPa pressure improves the particle density and water absorption. The filling of air voids in the poor residual attached cement provides these improved properties. The formed calcium carbonate take the place of air voids, hence density is increased as a result of filling more material into the same space. Secondly, water absorption is lowered as the formed materials block the entrance of water from getting into air voids. Crushing value is also reduced as a result of the increased density.

3.4.2. *Experimental and mix design*

The testing for CO$_2$ Concrete before and after carbonation shall be tested for recycled aggregate replacement percentages of 0 and 100% in laboratory scale in accordance with AS 1012.9. However, by the nature of living labs, the biosecurity platforms as well as cattle drinking station slabs will always utilise at least a percentage of carbonated recycled concrete aggregate in order to examine the unknown material to the fullest whilst only possessing a finite number of samples. The biosecurity samples, consequently, contain 100% recycled aggregate replacement with virgin aggregate. The cattle drinking station slabs use both a 15% and 100% carbonated recycled aggregate replacement with virgin aggregate concrete to enable a comparison whilst still employing CO$_2$ Concrete for all living labs. All carbonated concrete samples are carbonated for 1 h at 25 kPa, permitting a practical carbonation of aggregate. The practical parameters are based on an acceptable duration for commercial concrete to be produced while allowing for a duration of effective carbonation. Carbonation variables can sequester 1% CO$_2$ based on the weight of recycled aggregate. The water to cement ratio of 0.4 allows for a good balance of mechanical performance and workability of fresh concrete. The cement content is based upon the properties of the other constituents of the concrete mixture. Table 2 demonstrates the recycled aggregate replacement for each experiment whilst Table 3 shows the mix design used. Aggregate is replaced by mass.

3.5. *Concrete testing*

The application of CO$_2$ Concrete was investigated through three primary methodologies. The mechanical property examination including the 28-day compressive strength test is to be completed for both mechanical testing and both living labs. The implementation of non-destructive testing utilising rebound hammer analysis and the visual assessment shall be the final two methodologies utilised in the analysis solely for the living lab concrete.

3.5.1. *Testing based on Australian standard*

AS 1012.9 outlines the procedure for obtaining the compressive strength of concrete and was the only Australian standard employed in the practical living lab investigation. The rate of loading for such an examination is 20 ± 2 MPa per minute. Accordingly, the concrete mixtures permit supplementary materials for the casting of additional concrete cylinders 100 mm in diameter and 200 mm high. The concrete cylinders were deployed for testing after 28 days. All the results obtained from the compressive strength test are averages of three separate values.

3.5.2. *Non-destructive examination*

Non-destructive examination of a concrete applied in a real-life situation is carried out with the help of a Schmitt or rebound hammer. The rebound hammer employed in this investigation was manufactured by CIVILAB Australia. The hammer was specifically of Type N, and is suitable for examination of standard concretes above the thickness of 100 mm. The methodology employed in the non-destructive examination was given by the manufacturer, and is largely similar to that prescribed in ASTM C805/C805M (Standard Test Method for Rebound Number of Hardened Concrete).

The procedure involves comparing the reading predicted by the hammer with the results obtained by destructive examination of the compressive strength. In the case of this investigation, the use of the rebound hammer on a horizontal plane provided accurate compressive strength values. To obtain an accurate estimate, the final results must be an average of the results of 10–15 individual rebound hammer tests.

3.5.3. *Visual inspection*

Though not connected to the standard laboratory procedure, visual inspection of concrete is invaluable, as has been confirmed through past research (Merejo, 2013) (Chang, 2013). The optical evaluation of concrete involves identifying any possible degradation or failure mechanisms. The evaluation is completed over time; periodical inspections are

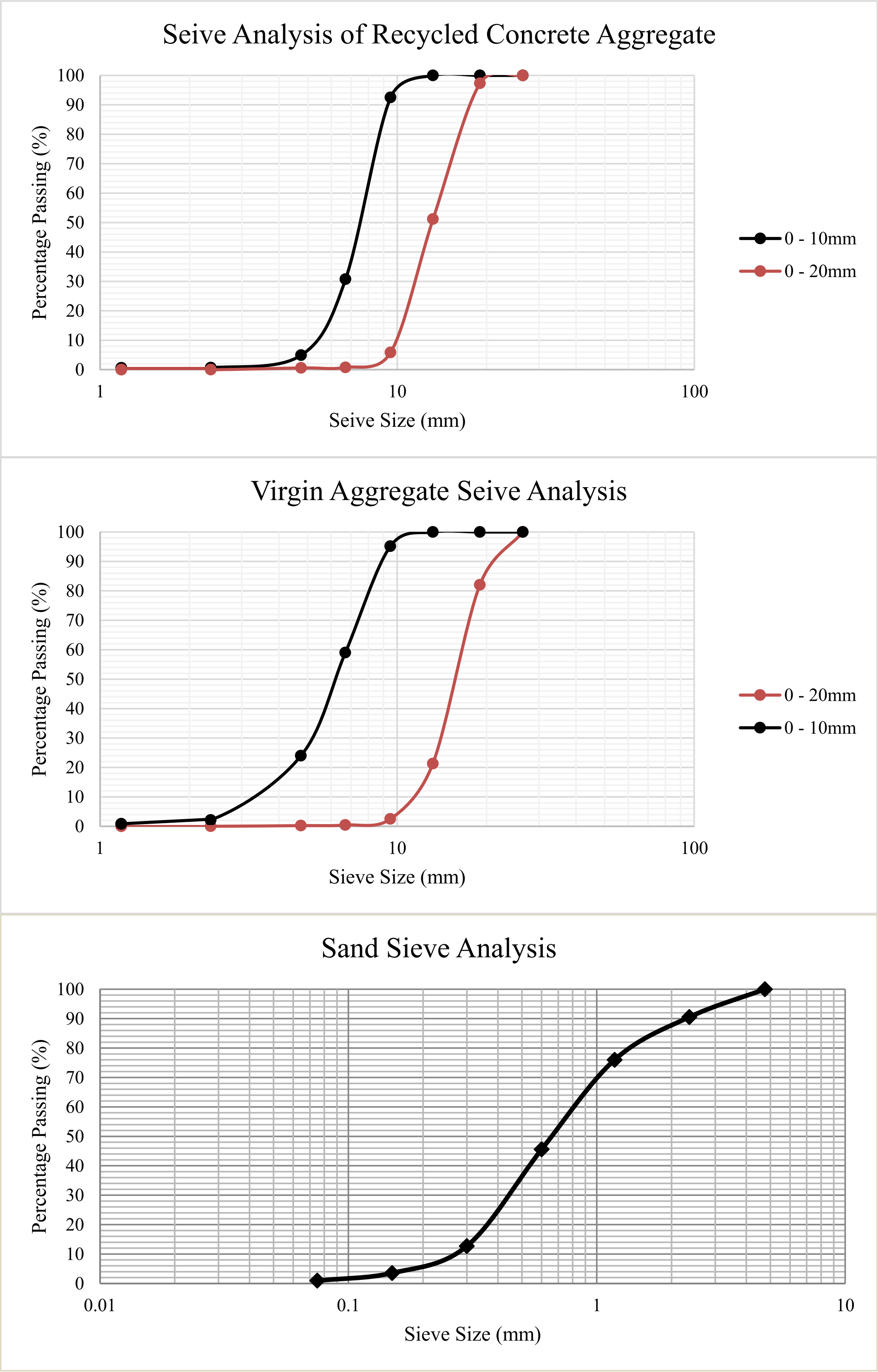

Fig. 3. Sieve analysis.

appropriate for identifying possible degradation.

4. Results and discussions

4.1. Mechanical property of laboratory CO_2 concrete

The mechanical property of recycled aggregate concrete is greatly improved after the accelerated injection of CO_2. Fig. 4 demonstrates the compressive strength of CO_2 Concrete as well as recycled aggregate concrete against virgin aggregate concrete (see Fig. 5).

Fig. 4 uncovers information that extends upon as well as confirms the works of previous researchers. The untreated recycled aggregate concrete experienced a loss of compressive strength of 35%; confirming a common characteristic amongst 100% recycled aggregate concretes,

Table 1
Size distribution, particle density, absorption and crushing value of aggregate before and after carbon-conditioning.

Aggregate	Particle Density						Absorption				Crushing
	Apparent Particle Density (t/m³)		Particle Density on Dry Basis (t/m³)		Particle Density on Saturated Surface Basis (t/m³)		Water Absorption (%)		Moisture Content (%)		Crushing Value (%)
	10 mm	20 mm	10 mm	20 mm	10 mm	20 mm	10 mm	20 mm	10 mm	20 mm	13.2–9.5 mm
Virgin Aggregate	2.81	2.98	2.63	2.78	2.70	2.84	1.41	1.41	0.97	0.99	16.65
Recycled Aggregate	2.69	2.65	2.19	2.24	2.37	2.39	7.49	5.89	0.90	1.06	27.26
Carbonated Recycled Aggregate	2.71	2.68	2.28	2.35	2.46	2.50	3.54	2.49	0.96	0.98	25.95

Table 2
Experimental design for CO_2 Concrete slab.

Concrete Variable	Recycled Aggregate Replacement (%)	
Mechanical Properties (Laboratory Core Samples, AS 1012.9)	0	100
Security Platforms	100 Quantity: 2	
Cattle Drinking Station Slabs	15 Quantity: 2	100 Quantity: 2

*All carbonated materials experience a carbonation duration of 1 h and pressure of 25 kPa.

typically lowering by 30% (Batayneh et al., 2007) (Rahal, 2007). The poor mechanical quality is attributed to the poor characteristics of recycled aggregate when compared to virgin aggregate. Table 1 indicates the poor property of the aggregate showing the recycled aggregate is less dense, has an increased water absorption and, furthermore, has additional weak interfacial transition zones when compared to virgin aggregate (Pacheco et al., 2019) (Omary et al., 2016).

The standard deviation is 1.53, 2.28 and 2.12 for the virgin aggregate concrete, CO_2 Concrete and untreated recycled aggregate concrete, respectively. This can be observed in the error bars found in Fig. 4. Furthermore, this shows that the virgin aggregate is more consistent than the recycled aggregate concrete. This is a result of the range in quality of recycled aggregate when compared to the virgin aggregate material.

CO_2 Concrete mitigates many of the negative properties associated with recycled aggregate as the aggregate is made denser. The chemical reaction for the densification of recycled concrete aggregate is located below.

$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$ (1) Carbonation Reaction (Zhan et al., 2014)

Fig. 4 illustrates the outstanding improvement of laboratory CO_2 Concrete, almost attaining the compressive strength of the virgin aggregate concrete only facing a 5% reduction but a large improvement over the recycled aggregate concrete. The performance can be attributed to the conversion of calcium hydroxide to the calcium carbonate by the CO_2. The transformation increases density as well as lowering water absorption, subsequently, improving upon the final concrete performance. The upwards trend can be found within previous research (Zhang et al., 2015) (Kou et al., 2014a) (Xuan et al., 2017).

The improvement of CO_2 Concrete exhibits the idiosyncrasies required for larger scale concrete use. However, the unscaled employment of CO_2 Concrete has not yet been investigated. The following sections demonstrate the ability of CO_2 Concrete in two living lab scenarios.

Table 3
Mix design for recycled aggregate concrete.

Recycled aggregate replacement ratio	Cement (kg/m³)	Water (kg/m³)	Water-to-cement ratio	Sand (kg/m³)	10 mm virgin aggregate (kg/m³)	20 mm virgin aggregate (kg/m³)	10 mm recycled aggregate (kg/m³)	20 mm recycled aggregate (kg/m³)
0%	525.00	210.00	0.4	632.70	344.10	688.20	–	–
15%	525.00	210.00	0.4	623.70	292.49	584.97	51.62	103.23
100%	525.00	210.00	0.4	632.70	–	–	344.10	688.20

*The biosecurity platforms use 300 mL of admixture for 100 kg/m³ of cement.

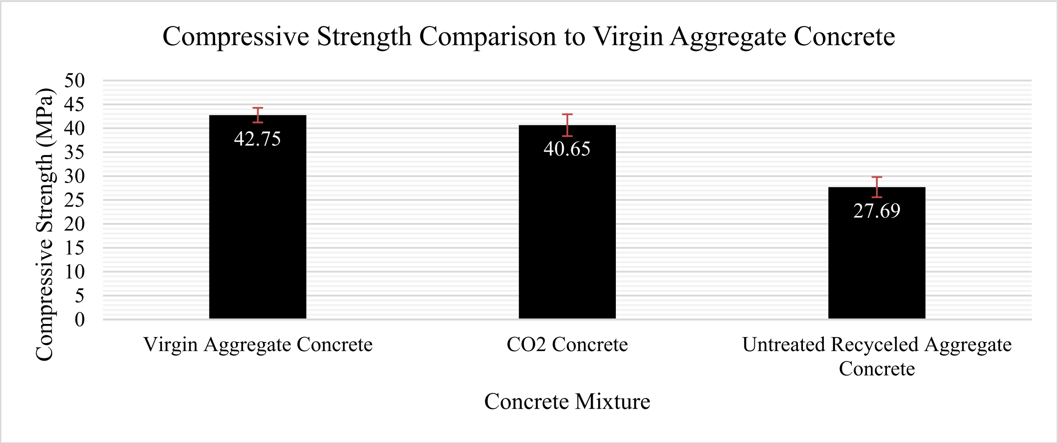

Fig. 4. Compressive strengths for concrete before and after carbon-conditioning.

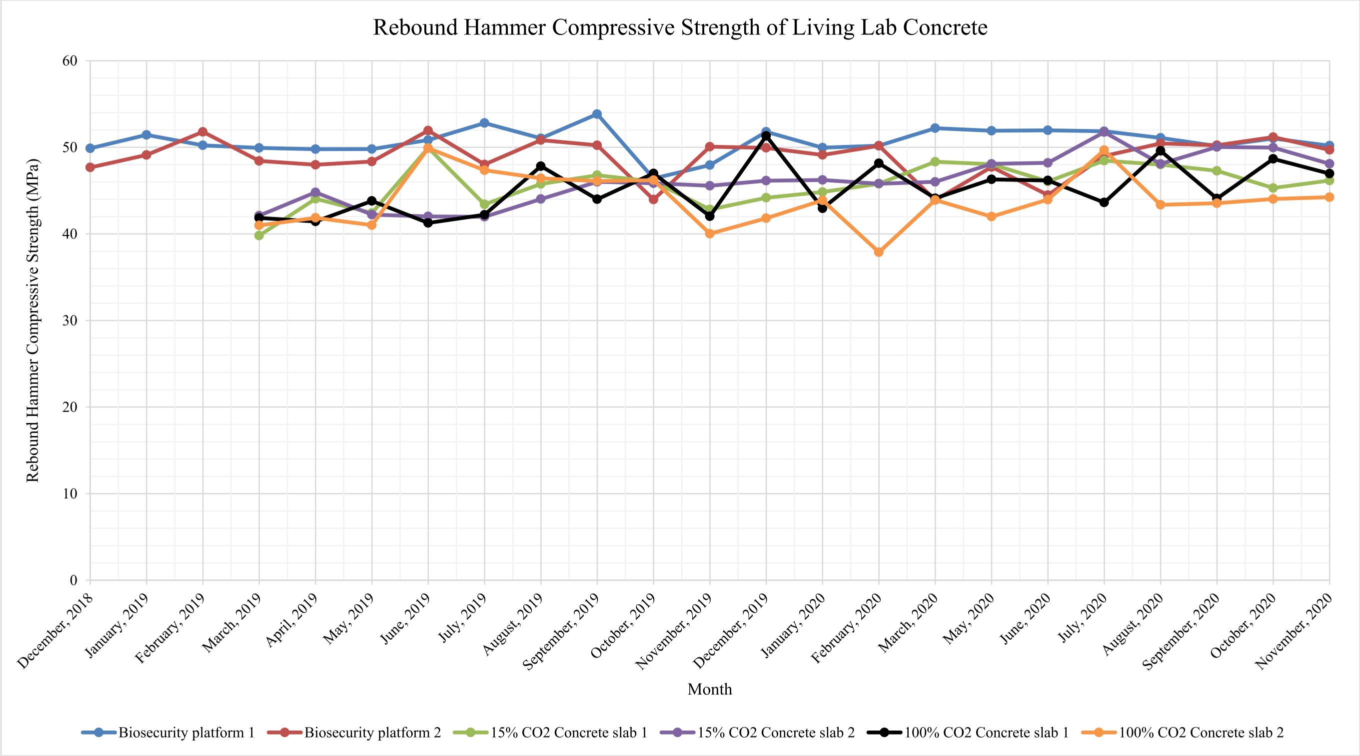

Fig. 5. Rebound compressive strength of CO2 Concrete for biosecurity platforms and cattle drinking station slabs.

4.2. *Compressive strength of biosecurity platforms and cattle drinking station slabs*

The 28-day compressive strength of both the biosecurity platforms and cattle drinking stations slabs is admirable. Table 4 shows the mechanical quality of the CO_2 Concrete.

4.2.1. *Biosecurity platforms*

The accomplishment of the platforms endorses the findings of previous researches (Zhang et al., 2015) (Zhan et al., 2013) (Xuan et al., 2016a). Biosecurity platform 1 attained a gain in strength (46.35 MPa) when compared to the virgin aggregate control (42.75 MPa) with platform 2 (42.43 MPa) attaining a very similar result to the virgin aggregate laboratory concrete found in Fig. 4. The formation of supplementary calcium carbonate provides the strengthening of recycled aggregate concrete, however, the addition of chemical admixture can explain the further increase in compressive strength when rivalled against the plain laboratory CO_2 Concrete. The plasticiser can assist with the placement of the concrete whilst the air entrainment additive can provide small strength gains (Neville, 2012) (Koren and Hall, 2012). However, the initial compressive strength only provides an indication of the effectiveness of the concrete prior to its practical use. For observation of the CO_2 Concrete in a practical situation, both non-destructive testing and periodical visual inspections are given the highest considerations.

Table 4
Compressive strength of CO_2 Concrete for biosecurity platforms and cattle drinking station slabs compared to virgin aggregate concrete.

Concrete applications	Average Compressive Strength (MPa)	Standard Deviation
Biosecurity platform 1	46.35	0.39
Biosecurity platform 2	42.43	1.42
15% CO_2 Concrete slabs	42.31	0.76
100% CO_2 Concrete slabs	40.57	1.59

*28-Day Strength. The excess materials for both mix designs for the 15% and 100% recycled slabs reflect two slabs having identical mix designs.

4.2.2. *Cattle drinking station slabs*

Similar to the case of the biosecurity platforms, the 28-day compressive strength only provides an indication of the practical performance of the cattle drinking station slabs. The compressive strengths of the slabs are 42.31 and 40.57 MPa for the 15% and 100% recycled aggregate concretes, respectively. The 15% slabs attain a greater strength as they are quite similar in content to the virgin aggregate control of Fig. 4. The impact of carbon-conditioning on the 15% CO_2 concrete is not as great as the 100% recycled aggregate material as there is simply a smaller amount of aggregate that is carbonated. The 100% CO_2 concrete slabs are very similar to the findings within the previous section characterised by a 5% loss in performance when compared to the virgin aggregate control but surpassing the recycled aggregate control found in Fig. 4. The 100% CO_2 concrete slabs experience a greater gain in strength due to the amount of recycled aggregate material. The slight devaluation of compressive strength when compared to the biosecurity platforms can be attributed to the removal of chemical admixture.

4.3. *Non-destructive examination of biosecurity platforms and cattle drinking station slabs*

The non-destructive examination of the living labs permits the indication of compressive strength throughout the concrete lifespan. The non-destructive testing allows the evaluation of ageing, which provides a window into the concrete durability as well as the effect of natural agricultural interactions. Table 5 demonstrates the preservation of strength exhibited by the CO_2 Concrete under harsh agricultural conditions.

4.3.1. *Biosecurity platforms*

The rebound hammer compressive strengths of both the biosecurity platforms represent improvements over the initial virgin aggregate

Table 5

Rebound compressive strength of CO_2 Concrete for biosecurity platforms and cattle drinking station slabs.

Concrete application →/Rebound compressive strength (MPa) ↓	Biosecurity platform 1		Biosecurity platform 2		15% CO_2 Concrete slab 1		15% CO_2 Concrete slab 2		100% CO_2 Concrete slab 1		100% CO_2 Concrete slab 2	
	Compressive Strength	Standard Deviation	Compressive Strength	Standard Deviation	Compressive Strength	Standard Deviation	Compressive Strength	Standard Deviation	Compressive Strength	Standard Deviation	Compressive Strength	Standard Deviation
December 2018	49.9	1.3	47.7	1.3	–	–	–	–	–	–	–	–
January 2019	51.4	1.3	49.1	1.4	–	–	–	–	–	–	–	–
February 2019	50.2	1.2	51.8	1.3	–	–	–	–	–	–	–	–
March 2019	49.9	1.3	48.4	1.3	39.8	1.3	42.1	1.4	41.8	1.3	41.0	1.4
April 2019	49.8	1.3	48.0	1.3	44.1	1.3	44.8	1.3	41.4	1.2	41.9	1.3
May 2019	49.8	1.3	48.4	1.3	42.4	1.3	42.2	1.3	43.8	1.3	41.0	1.3
June 2019	50.8	1.3	51.9	1.3	49.9	1.4	42.0	1.4	41.3	1.4	49.9	1.5
July 2019	52.8	1.8	48.0	1.3	43.4	1.4	42.0	1.4	42.2	1.5	47.4	1.3
August 2019	51.0	1.3	50.8	1.3	45.8	1.3	44.0	1.4	47.8	1.3	46.4	1.3
September 2019	53.8	1.0	50.2	1.5	46.8	0.9	46.0	1.6	44.0	1.6	46.1	1.1
October 2019	46.4	0.9	44.0	1.2	46.0	1.3	45.9	1.0	47.0	1.1	46.2	1.2
November 2019	47.9	1.1	50.1	0.8	42.8	1.2	45.6	1.3	42.0	1.5	40.0	1.0
December 2019	51.8	1.5	49.9	1.1	44.2	1.0	46.1	0.8	51.3	1.1	41.8	1.0
January 2020	50.0	1.2	49.1	1.1	44.8	1.2	46.2	1.1	43.0	1.3	43.9	1.2
February 2020	50.2	1.5	50.2	1.2	45.8	1.4	45.8	1.9	48.2	1.5	37.9	1.8
March 2020	52.2	1.3	43.9	1.4	48.3	1.8	46.0	2.0	44.1	1.7	43.9	1.4
April 2020	–	–	–	–	–	–	–	–	–	–	–	–
May 2020	51.9	1.6	47.7	1.6	48.0	1.8	48.1	1.9	46.3	1.5	42.0	1.7
June 2020	52.0	1.5	44.5	1.1	46.0	1.4	48.2	1.5	46.2	1.5	44.0	1.6
July 2020	51.9	1.3	49.0	1.1	48.5	1.3	51.8	1.6	43.6	1.6	49.7	1.7
August 2020	51.1	1.0	50.4	1.0	48.0	2.0	48.1	1.2	49.6	1.4	43.4	1.6
September 2020	50.1	1.5	50.2	1.6	47.3	1.3	50.0	1.7	44.1	1.6	43.5	1.3
October 2020	51.0	1.8	51.2	1.1	45.3	1.4	50.0	2.0	48.7	1.5	44.0	2.0
November 2020	50.2	1.0	49.7	1.6	46.2	1.2	48.1	1.5	47.0	1.5	44.2	1.3

*All the results are averages of the results of 15 separate tests. The biosecurity platforms were produced in March 2018 and subjected to non-destructive testing only after the equipment became available. The slabs were produced in the final days of February 2019. Testing could not be conducted during the month of April 2020 due to COVID 19 restrictions.

control (Table 5). The improvement in strength can be attributed to continued hydration of the concretes cement paste. Furthermore, the biosecurity platforms contain a cement with 30% fly ash, a supplementary cementitious material that assist with improvement of concrete durability (Mengxiao et al., 2015). The combination of carbon-conditioning of aggregate and fly ash in the new cement permit the maintenance of strength, overcoming the challenges of practical use. In the case of the biosecurity platforms, the external influences during usage include outdoor weather, varying live loads, abrasion by boots, movement of the concrete around the agricultural land, contact with heavy fauna (cattle), possible exposure to agricultural chemicals and additional unknown experiences due to external stakeholders. The external factors can significantly affect the quality of the concrete when located within the field (Al-Tabbaa et al., 2019). Consequently, the carbon-conditioning process can help the biosecurity platforms to preserve and even improve their mechanical properties, especially when compared to laboratory virgin aggregate and recycled aggregate concrete.

The strengths of the biosecurity platforms peaked during the month of September 2019, before small decreases were observed in the subsequent months. Nevertheless, the decreases are slim and further non-destructive experimentation is required in order to confirm if greater degradation of the platforms will occur in the following months or years. However, the concretes performance is desirable considering the conditions.

The biosecurity platforms preserve their compressive strengths even when subjected to harsh agricultural conditions. However, compressive strength is not the only factor governing concrete quality, with visual inspection revealing additional information.

4.3.2. *Cattle drinking station slabs*

The non-destructive examination began a month after the production of the four slabs. The slabs containing 15% and 100% CO_2 Concrete displayed similar results, with the strengths being similar over the duration of experimentation as located in Table 5. The cattle drinking station slabs are beginning to surpass the 28-day strength of the laboratory virgin aggregate concrete (Fig. 4) as of August 2019, which is extremely positive, however they have not realised the same success as the biosecurity platforms.

The cattle drinking station slabs, after a month of hydration, experience greater challenges than the biosecurity platforms. The slabs experienced the same trials as the platforms but the loads extended further to herds of cattle standing on top of them, each of which can weigh up to a tonne, the placement of a 2.6 tonne water drinking basin and the movement of heavy agricultural machinery driving over. Furthermore, the slabs do not contain fly ash or chemical admixture which the biosecurity platforms have the benefit of. These factors do not allow the slabs to achieve the same performance as the biosecurity platforms. The cattle drinking station slabs have displayed an outstanding preservation of strength based upon the challenging nature of their exposure. Similar to the biosecurity platforms the durability can be attributed to carbon-conditioning.

The 100% recycled aggregate CO_2 Concrete slabs achieved a similar performance to the 15% recycled aggregate CO_2 Concrete slabs. This is due to the amount of aggregate carbonated. The 100% recycled aggregate CO_2 Concrete slabs achieve a greater strength gain as there is more material to be carbonated. The 15% recycled aggregate CO_2 Concrete slabs only have a small amount of material to carbonate and consequently do not see much of an improvement due to carbon conditioning. The 15% CO_2 Concretes has a larger majority of basalt and therefore achieves a very similar result to the laboratory virgin aggregate concrete.

The injection of CO_2 improves the porosity and water absorption of the aggregate, brandishing a high density as well as minimal free water movement. These characteristics contribute to the reduction of concrete shrinkage allowing for a durable concrete (Mastali et al., 2018) (Guo et al., 2018) (Xuan et al., 2017).

4.4. *Visual inspections of biosecurity platforms and cattle drinking station slabs*

Figs. 6–11 demonstrate the ability of CO_2 Concrete to be utilised in a practical, real-life situation. Fig. 12 displays some images of interest, including cattle interacting with the slabs.

4.4.1. *Biosecurity platforms*

Visual inspection resulted in the images shown in Figs. 6 and 7. The images permit visual identification of the degradation occurring over a complete year and a half of real agricultural life. In compliance with the results of the non-destructive examination, the biosecurity platforms successfully maintained their quality. The surfaces of both the biosecurity platforms are of a high quality, not showing cracks of any kind, including those due to shrinkage, surface abrasion, chemical attack or loss of surface material. The preservation of an excellent surface area over a long period of time indicates a high-quality concrete which is characterised by great durability (Ulm, 2013) (Guo et al., 2018).

After a year of practical use, the only reduction in quality which can be visually identified is the insignificant loss in the sharp, external, top edge. Over time, the sharp edge becomes slightly rounded, predominantly due to surface abrasion, which most likely occurs during the scraping of shoes on the edge of the concrete which is visible in Figs. 6 and 7. This can only be observed during practical implementation, and the living lab permits external stakeholders to use the biosecurity platforms by natural means (Gascó, 2017) (Evans et al., 2015). The scrapping of shoes along the edge of the concrete is a product of the agricultural personnel's attempts to remove large amounts of debris from the tread of their boots. Nevertheless, the edge of the concrete is still in acceptable condition after a full year of use.

The properties bestowed upon CO_2 concrete through carbon-conditioning result in an outstanding overall performance, which is transferable to practical scenarios. Whilst the biosecurity platforms provide compelling evidence for the practicality of CO_2 Concrete, the four cattle drinking station slabs present an even greater challenge for the sustainable replacement material.

4.4.2. *Cattle drinking station slabs*

The visual inspection of the cattle drinking station slabs reveals an absence of any sort of degradation. The slabs are free from cracks, surface abrasion or chemical attacks. All slabs have experienced loads of both the cattle water drinking basin which weighs 2.6 tonnes when full of water as well as the weight of up to 5 cattle. Considering the circumstances, the CO_2 Concrete slabs are very impressive, as they do not reveal signs of degradation, particularly with herds of cattle moving on top of the surface. The performance of the CO_2 Concrete slabs can be attributed to the overall quality attainment instilled by the carbon-conditioning process. The increase in durability of carbonated recycled aggregate is supported by previous research (Xuan et al., 2017) (Guo et al., 2018) (Li et al., 2019).

Fig. 12 shows the slabs in use. Images A, B and C show a variance of cattle drinking water. The largest of the cattle, observable in picture C, weigh approximately 1 tonne. This is a good low risk application whilst putting the new technology to the test. Cattle are typically rotated from paddock one to four (each slab goes in one paddock) and consequently each slab experiences some time with cattle drinking on top of them. Whilst paddocks are empty, crops are grown. Heavy tractors are implemented in the working of these crops and consequently these machines drive over the concrete slabs. Image D shows a tyre track from heavy machinery. The image shows no sign of degradation upon harsh agricultural treatment.

The CO_2 Concrete slabs establish that the recycled concrete can be utilised as a replacement to virgin aggregate concrete. Further research can be implemented in order to demonstrate CO_2 Concretes ability in a

Fig. 6. Biosecurity platform 2 visual inspections.

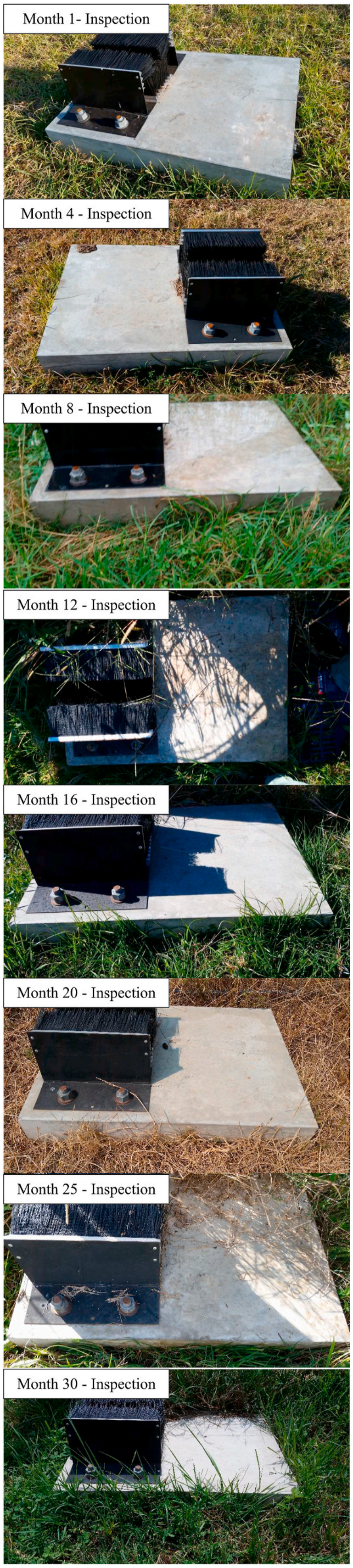

Fig. 7. Biosecurity platform 1 visual inspections.

Fig. 8. 15% CO_2 concrete slab 1 visual inspections.

Fig. 9. 15% CO_2 Concrete slab 2 visual inspections.

Fig. 10. 100% CO_2 Concrete slab 2 visual inspections.

Fig. 11. 100% CO_2 Concrete slab 1 visual inspections.

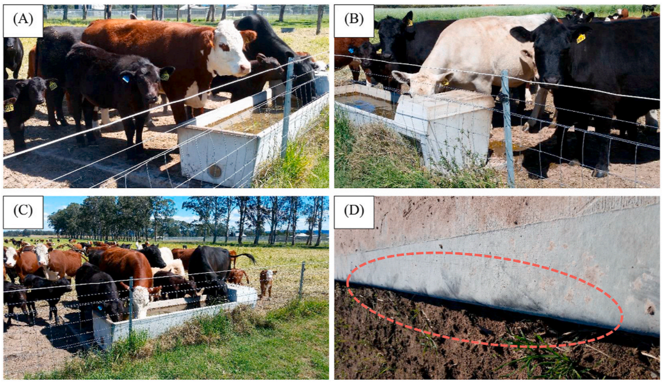

Fig. 12. Images of interest. Images A,B and C show cattle standing on the slab. Image D shows a tyre track from a tractor (inside red circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

structural situation. These slabs show that CO_2 Concrete can be successfully implemented into a living lab scenario.

5. Conclusion

Carbon-conditioning is an effective process for improving the mechanical quality of both recycled aggregate and recycled aggregate concrete. The application of CO_2 Concrete into a real-life situation or living lab is entirely possible as the concrete displayed no sign of weakness when faced against unforgiving agricultural use. The use of CO_2 Concrete on a larger scale has immense potential as exhibited within the success of the living lab. However, the CO_2 Concrete does require a longer period of time to ensure the durability of the concrete is acceptable. CO_2 Concrete can replace virgin aggregate concrete in the future to create a sustainable and strong concrete product. The following points highlight the findings of this paper.

- After carbonation the CO_2 Concrete biosecurity platforms, achieved 46.35 MPa and 42.43 MPa respectively, exhibiting a similar 28-day compressive performance to the virgin aggregate concrete of 42.75 MPa.
- The cattle drinking station slabs attained a 28-day strength of 42.31 MPa and 40.57 MPa.
- The biosecurity platforms containing 100% of carbonated recycled aggregates reveal good performances for more than 2 years of practical use in the agricultural environment The only degradation found in the biosecurity platforms is the very slight rounding over of the edges due to the rubbing of boots to remove large debris.
- The cattle drinking station slabs containing both 15% and 100% CO_2 Concretes display great practical performances which are nearly identical.
- No degradation or loss in the compressive strength is observed in the slabs even with heavy cattle and tractor use on top of the slabs.

The combination of successful application of CO_2 Concrete to a practical situation and analysis of the mechanics of the material reveals the potential of the sustainable material to be an acceptable alternative to the typical virgin aggregate concrete. CO_2 Concrete exhibits desirable characteristics which can be utilised in future development of concrete infrastructures.

Declaration of competing interest

There is no conflict of interest for this paper.

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