

The use of Fungus as CO₂ Sequestration: A Systematic Review

Amar Aiman Mohamad Pauzi¹, Mohd Irwan Juki^{2*}, Abdullah Faisal Abdulaziz Al-Shalif¹, Saddam Hussein Ali Abo Sabah¹

¹Faculty of Civil Engineering and Built Environment,
Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, 86400, MALAYSIA

²Jamilus Research Centre (JRC), Faculty of Civil Engineering and Built Environment,
Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, 86400, MALAYSIA

*Corresponding Author Designation

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Abstract: Concrete is one of the important materials used in construction industry. Despite of its advantage in compressive strength, concrete also has its own disadvantage, namely that concrete is a material that easy to crack due to several factors. In addition, the manufacturing of concrete has brought a negative impact on the environment due to the emission of large amounts of carbon dioxide into the earth's atmosphere due to the production of cement in the factory. Previous research found that the amount of carbon dioxide can be capture or sequestrate by using fungus and transform into mineral through a bio mineralization process, where mineral such as calcium carbonate (CaCO₃) is precipitate in a condition where there is a presence of calcite in the environment. This study focused on effect of fungus on carbon dioxide sequestration in bio-concrete and also identified the factor affecting the rate of carbon dioxide sequestration in bio-concrete by using fungus as an added material by doing a systematic review. Data is selected from the eligible article and qualitative analysis is conducted to achieve the objective. Result of this research found that the effect of fungus in CO₂ sequestration bring positive feedback to the rate of CaCO₃ precipitation in bio-concrete and the factor affecting the rate of CO₂ sequestration in bio concrete using fungus is due to the concentration of carbon dioxide and also surface area of fungus used.

Keywords: Fungus, Carbon Dioxide Sequestration, Bio-Concrete, Self-Healing, Biomineralization

1. Introduction

Energy demand nowadays increasing due to the rapid growth of economic due to the expanding of human population. Increasing energy demand led to the increasing uses of fuel such as fossil fuel, which lead to the uncontrolled number of carbon dioxide (CO₂) emission into the atmosphere. In 2011, 33.4 billion tonnes of CO₂ are emitted globally, which is 48% higher than the last two decades and expected to increase more in the future. The emission of CO₂ and other greenhouse gases are

*Corresponding author: irwan@uthm.edu.my

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generally due to the increasing anthropogenic activity in the current century. One of the sources of carbon dioxide emission into the atmosphere is production of cement. Clinker manufacturing is well known as a contributor to the direct release of CO₂ where 60% of carbon dioxide release from this sector is come from calcination process and the other 40% are come from combustion process [1]. Climate change is one of the main topics discussed by many people in the twenty first century because of it is one of the biggest environmental concerns. The emission of CO₂ and other greenhouse gases are generally due to the increasing anthropogenic activity in the current century. The dependency on fossil fuel has brought implication of emission of greenhouse gases (GHGs). It is estimated around 6511 metric tonnes of carbon dioxide equivalents (CO₂e) is emitted from the greenhouse gases in United State in 2016 [2]. As much as 5-7% of total anthropogenic carbon dioxide emission comes from the manufacturing of cement [3]. Table 1 shows the type of gases emmited per year.

Concrete can be classified as a composite material, which is the product of mixing of some material. In many years, construction industry has been taken this opportunity seriously and uses it wisely and become a fundamental material that used to construct a construction that related to buildings. This is due to the availability access to purchase the raw material that needs to be used to produce a good concrete product and economic cost for work with it. Concrete consists of several material such as cement, aggregate, water, and some additive to enhance their characteristic itself. The addition of additive in the cement mixture will improve the cementitious properties due to the pore-filling effect of the material and increase the tensile strength, specific surface area and elastic modulus [4]. There are several advantages of concrete that attract interest of many contractors to use it as the main material, which are concrete has high compressive strength, durable to any extreme environment, availability, versatility, compatibility with reinforcement bar, a great fire-resistance, low in price, ease of fabrication, and the ability to be moulded into different shape [5].

Table 1: The masses of emitted CO₂ and other pollutants produce in the European cement kilns per year [3]

Pollutant	Mass emitted (tonnes per year)
CO ₂	1.5456 million
CO	460-11500
SO ₂	Up to 11125
NO _x as NO ₂	334-4670
Dust	0.62-522
TOC/VOC	2.17-267
HCl	0.046-46
HF	0.21-23.0
PCCD/PCDF	0.0000276-0.627 g per year

1.1. Fungus

Fungus is stated to be the most species rich group of eukaryotic organisms after insect with magnitude of diversity estimated around 1.5M to 3.0M species [6]. Fungus can be identified as a nonchlorophyllous and heterotrophic organism due to the required sources of carbon in nature to growth by eating food from dead organic matter (saprophytic) or from the autotropic/heterotrophic associates (parasitic and symbiotic) [7]. In previous year, the application of fungus in construction industry such as concrete manufacture has been in a highlight by many research.

Yeasts, lichen-forming fungus, molds, and mushrooms are the well-known fungi that can easily access in the world [8]. Most investigation that related to the fungus has been conducted due to their important role in organic matter degradation, and its relationship with the inorganic matter that has been focusing on mineral nutrition via mycorrhizal symbiosis, the production of myogenic organic acids, and lichen bio weathering [6]. Living things like green plant absorb CO₂ and convert it into oxygen that need by other living things such as animal and human by a process call photosynthesis. Same goes to the fungus; it also can undergo a process of CO₂ absorption and change it into a mineral

through a process call bio mineralization. In studies show that fungus are able to catalyse calcium mineral precipitation on crack in concrete structure [6].

1.2. Bio-concrete

In recent year, researchers are working hard to produce a solution to the cracking problem in concrete due to several factors. The cost of repairing the crack is more expensive than the making of the concrete. It has been estimated that the direct cost of concrete crack repair is at \$147 per m² of concrete compared to the production of concrete which is cost at range between \$65 to \$80 per m² [5]. During the past decade, a lot of research has been conducted to understand well on how crack can heal itself without human interference [9]. Bio-concrete can be defined as a self-healing concrete that design to repair its own crack without any help from human. There are 3 methods used to construct a self-healing concrete which by autogenous healing, encapsulation of polymeric material, and biological induced mineralization of calcium carbonate (CaCO₃) [5], [6], [8], [9]. This new approach of concrete that utilizing bacteria to produce a mineral precipitation will help to increase the strength and durability of concrete and at the same time can heal the damaged such as crack inside or outside the concrete [10].

2. Methodology

A systematic review is a review of a clearly formulated question that uses systematic and reproducible method to identify, select and critically appraise all the relevant research, and to collect and analyse data from the studies that are included in the review.

The first stage of systematic review is a search has been carried out to find the article that related to the study topic by referring to the keyword. Figure 1 shows the diagrammatic representation of literature review process. Internet has provided a good database of article such as Scopus, ScienceDirect and another database that related to article database. In this study, search engine database Scopus has been selected as a medium to find the article that related with the study topic. Articles that need to be selected must contain keywords that have been discussed. Scopus database was chosen because of the availability access to the article worldwide and easy to access. It also considers as a reviewed literature's largest abstract and as a citation database, where a lots of academic papers, books, article review, and conference proceeding is located inside the database. An extensive and systematic search is conducted by using the Boolean technique and keywords under the "title/abstract/keyword" field in the database.

First keyword is inserted into the search engine, which is "concrete" and followed by the next keyword which is "carbon dioxide" and last keyword is "fungus". The entire article that related with the keywords is saved in form of Portable Document Format (PDF). After entering all the keywords, a total of 80 articles were identify and collected and prepare for the next step. In this article review process, two limitations are used to determine the corresponding target article. First limitation is by year and second limitation is by the type of document. The results were next filtered by "Document type" (e.g. article and review) and "Year" (e.g.2010-2020). After input all the limitation, 52 articles were excluded and lead to 28 articles remaining for the next stage which is screening process. In this process, abstract and article title is reviewed. The article's abstract that consists of 2 or more keywords is selected and as resulted, 10 articles were excluded and lead to 18 remaining articles that were taken for the next step which is full reading through the article to identify their eligibility of article and resulted to exclude 8 article and lead to the 10 final articles to be use in systematic review.

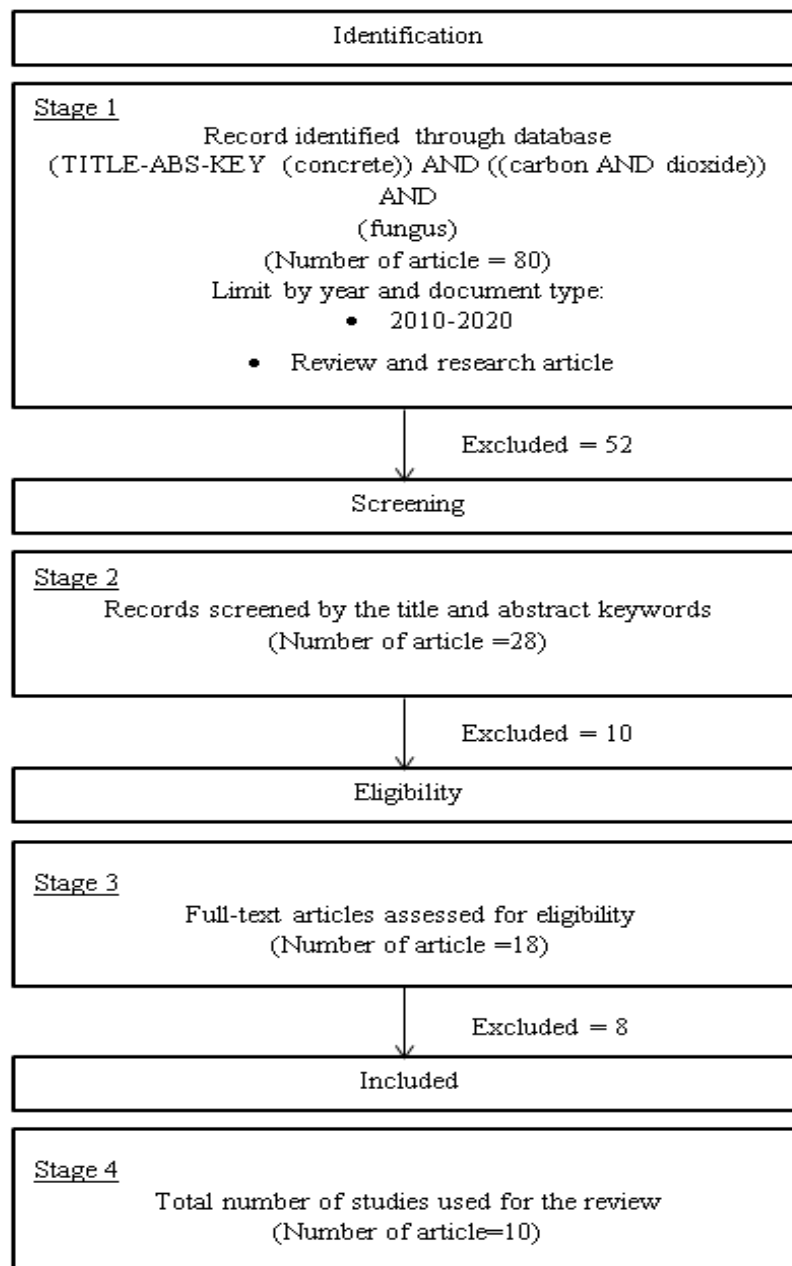


Figure 1: Systematic review flowchart process

3. Result and discussion

The data are collected from 4 different articles related to the study topic. The four articles are “Screening of Fungi for Potential Application of Self-Healing Concrete”, “Interactions of fungi with concrete: Significant importance for bio-based self-healing concrete”, “Potential of Fungi for Concrete Repair”, and “Study on the behaviors of fungi-concrete surface interactions and theoretical assessment of its potentials for durable concrete with fungal-mediated self-healing”. The data extract from these articles are type of fungus used in their investigation, pH value, temperature, and the precipitation of mineral inside the concrete medium.

3.1. Analyze of fungus activity in concrete

A comparison is made based on type of fungus used, pH value, type of testing, the surrounding condition parameter, and the existence of precipitate mineral. It found that in articles [6], [8], [12], and [12] stated that type of fungus used is filamentous fungus. These types of fungus consist of larger

surface area due to the filamentous body structure. Six fungi are purchased from American Type Culture Collection (ATCC), five fungi are collected from nature, eleven fungus collected from building structure, and other three types of fungus collected are not stated the sources, which is consider as unknown in Table 2. All articles' objective is same which to investigate the most suitable fungus used for self-healing purpose.

A series of testing to classify the type of fungus that can contribute to the precipitation of calcium carbonate (CaCO₃) for self-healing which are Scanning Electron Microscope (SEM) and X-Ray Diffraction (XRD). SEM worked as a tool to observe the crystalline precipitation in the sample while XRD contribute to the investigation of type of mineral form inside the precipitation. In articles [6], [8], and [11] stated that they used both testing to verify the mineral precipitation inside the fungus. In [12], the testing only consists of urease activity testing. All articles stated that the medium used is potato dextrose agar (PDA), Potato dextrose agar with addition of MOPS buffer made from 3-(N-morpholino) propanesulfanoic acid (MPDA), Potato dextrose agar with addition of concrete (CPDA), and Potato dextrose agar with addition of concrete and MOPS (CMPDA). The data collected are based on the CPDA medium, which it consists of extreme condition, which is have a dry and high pH value environment.

Table 2: Summary of type of fungus use in selected study case

Fungus	Sources of fungus	Type of fungus	Author	Year of publication
Aspergillus nidulans (ATCC38163)	American Type Culture Collection (ATCC)	Filamentous	Menon et al. [8]	2019
Aspergillus nidulans (MAD0305)	Unknown			
Aspergillus nidulans (MAD0306)	Unknown			
Aspergillus nidulans (MAD1445)	Unknown			
Aspergillus oryzae (ATCC1011)	American Type Culture Collection (ATCC)			
Aspergillus terreus (ATCC1012)	American Type Culture Collection (ATCC)			
Phanerochaete chrysosporium (ATCC24725)	American Type Culture Collection (ATCC)			
Rhizopus oryzae (ATCC22961)	American Type Culture Collection (ATCC)			
Cadophora interclivum (BAG4)	Pinus rigida (Roots of pitch pine)			
Pseudophialophora magnispora (CM14-RG38)	Carex sprengelii (subalpine forest)			
Trichoderma reesei (ATCC13631)	American Type Culture Collection (ATCC)	Filamentous	Luo et al. [6]	2017
Umbeliopsis dimorpha (PP16-P60)	Dichanthelium acuminatum (Rosette grass)			
Acidomelania panicicola (8D)	Panicum virgatum (Switchgrass)			
Aspergillus nidulans (ATCC38163)	American Type Culture Collection (ATCC)			
Phoma glomerata	Footbridge			
Cladosporium cladosporioides	Footbridge			
Valsa nivea	Footbridge			

Fusarium lateritium	Footbridge			
Phoma herbarum	Footbridge	Filamentous	Martuscelli et al. [11]	2020
Fusarium lateritium	Footbridge			
Coniochaetaceae sp.	Footbridge			
Cladosporium herbarum	Footbridge			
Phoma aliena	Footbridge			
Phoma saxea	Overpass			
Phoma saxea	Overpass			
Phoma saxea	Overpass			
Fusarium oxysporum	Unknown	Filamentous	Zhang et al. [12]	2021

3.2. Survivability and growth of fungus

Carbon dioxide is an acidic substance and reaction of water with carbon dioxide produce carbonic acid. Concrete is a substance that consists of high concentration of hydroxide ion (OH⁻). Germination of fungus in a selected medium must comply with the characteristic of the fungus. In article [6] and [8] stated that the pH value affects the germination of fungus. Figure 2 shows the pH value of growth medium, and changes occur when fungus is located into the growth medium.

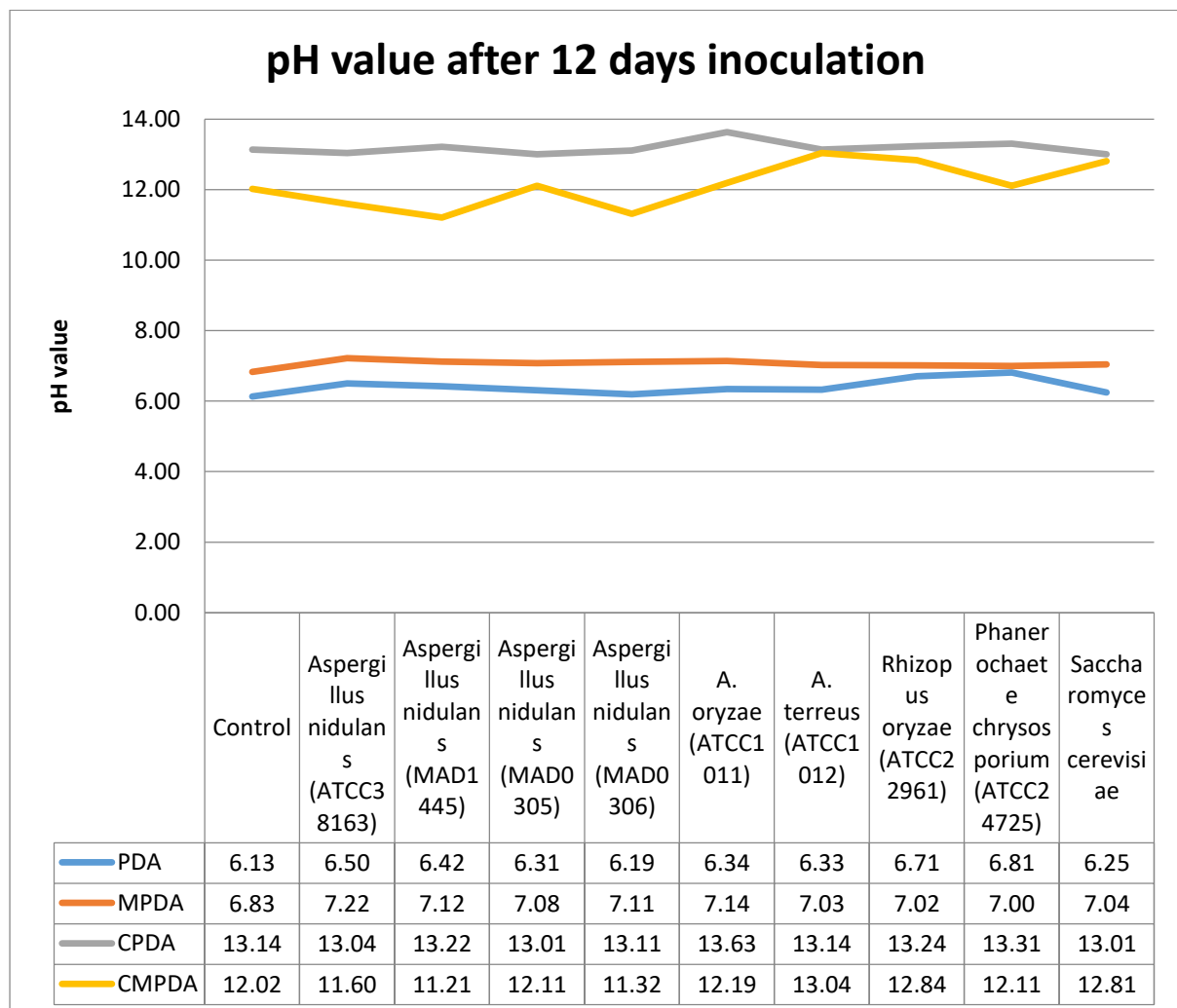


Figure 2: pH value of growth medium [8]

Table 3 and 4 show the growth of fungus in different medium proposed by Menon et al. [8] while Table 5 and 6 show the growth of fungus in different medium proposed by Luo et al. [6]. In term of CO₂ sequestration, some funguses are able to sequesterate CO₂ and precipitate CaCO₃. The temperature of growth medium affects the growth and precipitate of CaCO₃.

Table 3: CPDA 30 and CPDA 22 data [8]

Fungus	Growth		Precipitate of		pH difference	CO ₂ sequestration
	(mm/day)		CaCO ₃			
Rhizopus oryzae (ATCC22961)	x	x	x	x	0.1	x
Phanerochaete chrysosporium (ATCC24725)	x	x	x	x	0.17	x
Aspergillus nidulans (ATCC38163)	x	x	x	x	-0.1	x
A. terreus (ATCC1012)	x	x	x	x	0	x
A. oryzae (ATCC1011)	x	x	x	x	0.49	x
Aspergillus nidulans (MAD1445)	x	x	x	x	0.08	x
Aspergillus nidulans (MAD0305)	x	x	x	x	-0.13	x
Aspergillus nidulans (MAD0306)	x	x	x	x	-0.03	x

Table 4: CMPDA 30 and CMPDA 22 data [8]

Fungus	Growth		Precipitate of		pH difference	CO ₂ sequestration
	(mm/day)		CaCO ₃			
Rhizopus oryzae (ATCC22961)	x	x	x	x	0.82	x
Phanerochaete chrysosporium (ATCC24725)	x	x	x	x	0.09	x
Aspergillus nidulans (ATCC38163)	x	x	x	x	-0.42	x
A. terreus (ATCC1012)	x	x	x	x	1.02	x
A. oryzae (ATCC1011)	x	x	x	x	0.17	x
Aspergillus nidulans (MAD1445)	✓	✓	✓	✓	-0.81	✓
Aspergillus nidulans (MAD0305)	x	x	x	x	0.09	x
Aspergillus nidulans (MAD0306)	x	x	x	x	-0.7	x

Table 5: CPDA 30 and CPDA 25 [6]

Fungus	Growth		Precipitate of		pH difference	CO ₂ sequestration
	(mm/day)		CaCO ₃			
Trichoderma reesei (ATCC13631)	✓	x	✓	x	-0.1	✓
Aspergillus nidulans (ATCC38163)	x	x	x	x	-0.9	x
Cadophora interclivum (BAG4)	x	x	x	x	-1.1	x
Umbeliopsis dimorpha (PP16-P60)	x	x	x	x	-1	x
Acidomelania panicicola (8D)	x	x	x	x	-0.5	x
Pseudophialophora magnispora (CM14-RG38)	x	x	x	x	-1.1	x

Table 6: CMPDA 30 and CMPDA 25 [6]

Fungus	Growth		Precipitate of		pH difference	CO ₂ sequestration
	(mm/day)		CaCO ₃			
Trichoderma reesei (ATCC13631)	✓	x	✓	x	0.4	✓
Aspergillus nidulans (ATCC38163)	x	x	x	x	-0.6	x
Cadophora interclivum (BAG4)	x	x	x	x	-0.1	x
Umbeliopsis dimorpha (PP16-P60)	x	x	x	x	-0.2	x
Acidomelania panicicola (8D)	x	x	x	x	0.4	x
Pseudophialophora magnispora (CM14-RG38)	x	x	x	x	-0.5	x

3.3. Effect and factor affecting the rate of CO₂ sequestration in concrete

According to Luo et al. [6] and Menon et al. [8] in their article, 3 parameters is observe which are precipitation of CaCO₃, growth of fungus, and pH value of growth medium. In this research, it more focus on concrete medium, which consist of harsh environment, where the moisture content is low and high in pH value, where most of the fungus cannot germinate and grow. In study made by Menon et al. [8], growth of fungus leads to the precipitation of mineral through biomineralization process. To speed up the process, carbon dioxide from atmosphere is absorbed by the fungus through pore of the concrete. Carbon dioxide reaction with water will produce carbonic acid and when carbonic acid reacts with concrete, it will produce CaCO₃. In this case, Aspergillus nidulans (MAD1445) and Trichoderma reesei (ATCC13631) are successfully sequester the carbon dioxide to produce precipitate and reduce the pH value of growth medium.

Concrete heal is done by fungus through urease activity. The urea enzyme produce by fungus is used to precipitate mineral, which a product of reaction between urea enzyme, that produce carbon dioxide with leaching of Ca (OH)₂ from the concrete. This reaction promotes to the improvement of mechanical properties and durability of concrete [11]. A filamentous fungus is used due to the greater surface-to-volume ratio, which allow the fungus to interact with the substrate with a fast pace [12].

Increasing surface area help the fungus to absorb more carbon dioxide and increase the rate of biomineralization in concrete. Fungus is able to reduce the concentration of carbon dioxide in the atmosphere by sequestrate it into concrete and use it as a medium to increase the rate of biomineralization process. Another factor that affects the rate of carbon dioxide sequestration in concrete is high concentration of carbon dioxide.

4. Conclusion

Based on past research, the fungal are able to sequestrate the carbon dioxide in concrete medium and at the same time use the sequester product to do another process in concrete called crack healing by promoting the precipitation of CaCO_3 . This is supported by the result of pH value of *Aspergillus nidulans* (MAD1445) and *Trichoderma reesei* (ATCC13631), where there is decreasing number of pH value on the concrete growth medium and at the same time, these funguses are able to growth and precipitate mineral in a harsh condition, which is high in pH value. Some funguses are not able to withstand this kind of harsh condition and die. Effect of fungus in carbon dioxide sequestration in concrete is increase the rate of CaCO_3 precipitation while the factor affecting the rate of carbon dioxide sequestration in concrete are the type of fungus use which is filamentous fungus and concentration of carbon dioxide in the atmosphere also play important role for the fungus to absorb the carbon dioxide

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