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Limestone surface weathering cycles as the basis of circular architectural design

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ABSTRACT

This study explores the process of limestone weathering as the basis of a circular architectural design method. The natural process of limestone weathering enables neutralization of acid rainwater to improve the quality of the environment. By understanding weathering as a beneficial occurrence rather than unfavorable, this paper analyzes application of limestone material weathering for architectural design. The study identifies three different cycles in limestone weathering, such as the carbon cycle, the water cycle and the cycle of plant growth and decomposition. Based on these cycles, the natural arrangement of limestone surface, angle, depth and shape determines the continuous and discontinuous flows of elements; resulting in patterns of surface formation. Alteration of water flows potentially accelerates or slows down the cyclical phases, producing different environmental effects. The study develops architectural programming that neutralizes water for reforestation and recreation through limestone weathering. The design aims to maintain the limestone preserve, adding cultivation of coccolithophore algae into the natural limestone ecosystem. This design creates a circular system of weathering limestone to act as a carbon sink within the environment, regenerating the overall landscape.

Introduction

This study explores the process of limestone weathering as the basis of circular architecture. Weathering of limestone is a natural occurrence that happens to neutralize rainwater acidity in an environmental context. Limestone is a type of carbonate sedimentary rock originating from the deposit and calcification of mostly marine carbon matter (Wallmann et al. 2022). It can be found near oceans, lakes, rivers, springs or land areas that once contained a large volume of water. Buildings affected by weathering are normally seen as experiencing degradation (Çetintaş et al. 2022). This study highlights another perspective of weathering in architecture, by demonstrating the ability of weathered material to produce different effects that shape the overall design (Mostafavi and Leatherbarrow 1993). This paper studies how utilization of limestone weathering can be implemented as a method of design.

Weathering on limestone occurs due to interactions between different elements which create hollow shapes on the material. Such interactions demonstrate how natural processes, such as weathering, enable creation of forms (Allen 2013; Ball 2012). The limestone weathering is enabled by various forces in nature. Weathered surface material generates added value, fostering the maintenance process of life

(Alexander 2002). The cyclical process of limestone material weathering generates neutralized water and also exist as storage for carbon dioxide from the atmosphere. Such processes provide improvement to the surrounding natural environment. This study explores these processes and articulates its possibilities in developing circular architectural design.

Weathering, architecture, and circularity

This study explores how weathering influence architecture and how it may be used as the basis of circular design thinking. Designs that are disfigured from weather are normally regarded as an issue that needs to be solved. Architecture is perceived as a stable entity existing over time, disregarding weather, dirt and changes in the environment (Till 2013). If left to nature, weathering can cause severe structural, functional or aesthetic deterioration (Çetintaş et al. 2022; Mostafavi and Leatherbarrow 1993; Ye, Zhao, and Xu 2023). This leads to efforts done to minimize the impact of external weather on the final design by creating elements specifically to reduce the amount of weathering.

This study argues that consideration of weathering in the process of design may produce beneficial effects on the surrounding environment. Architects need to reconsider weathering as a potentially useful process of nature. Weathering is an inevitable outcome from the interaction of the design with the surrounding environment. Weathering has the capability to create finishes (Mostafavi and Leatherbarrow 1993). The value of the design increases as time passes (Alexander 2002), and therefore alternative perspective on enabling weathering to happen intentionally towards the design becomes necessary to reveal the qualities it can provide.

Weathering is the transformation created on materials due to its encounter with the environment. The surface material is affected by natural particles and weather patterns. The reaction can be chemical, mechanical or biological (Arman et al. 2019; Wild, Gerrits, and Bonneville 2022). These reactions produce different results based on the material that is exposed and the type of weather conditions. Chemical weathering happens when particles or reagents interact to form a product (Arman et al. 2019; Ball 2012). The substances interact at a molecular level to create change. On the other hand, during mechanical weathering, forces act physically on a surface that creates pressure to move, displace or split the material to a different location through cracking in duration of time depending on the characteristic of the material (Yang et al. 2023). Finally, biological weathering occurs when living agents change the form of the material. These living agents could grow on the surface such as plant roots or be in a state of decaying organic matter (Wild, Gerrits, and Bonneville 2022). Different types of weathering create different scales of changes and effects to the material in the built environment. Such process deforms the original shape through subtraction or addition of volume (Mostafavi and Leatherbarrow 1993). The process of weathering never reaches equilibrium, if it is open to the environment, there are always some effects on the material (Yang et al. 2023).

There are several forces in nature that take part in the process of weathering. Nature has an order of life, organizing and maintaining the stability of elements for a healthy ecological system that can be applied to architectural design (Alexander 2002; Rahman, Paramita, and Atmodiwirjo 2023). The environment is affected by human activities that change natural flow of natural elements (Paramita, Yatmo, and Saginatari 2022). Defects, imperfections and anomalies also exist as self– organizing emergent structures driven by weathering in nature; enhancing the value of life (Alexander 2002; Ball 2012). Analyzing the surrounding context of the occurrence of weathering can unravel the aspects that initiate the reaction. Continuous and discontinuous flows of processes in nature are encouraged by the conditions in the context (Allen 2013; Nabawi, Paramita, and Yatmo 2022). A continuous process occurs when the material is constantly affected by chemical, mechanical or biological weathering. The speed of the weathering process may happen at a faster or slower rate depending on the spatial conditions. Identifying patterns and logics of flows within the context shows the underlying process that takes place to trigger the reaction of weathering.

As the driver of weathering process, natural weather is a phenomenon that affects a certain environmental setting. Shifts in weather create patterns of different biogeochemical cycles; such as water cycle, carbon cycle and the cycle of plant growth and decomposition which determine the various impact of weathering. In this sense, weathering is not only influenced by exposure of a built environment to the weather, but also how the weather changes local conditions of the environment, and all the cycles within the ecosystem. The study explores how these cycles apply in the process of limestone weathering.

The water cycle maintains the hydrology needed by the environment through evaporation, precipitation and collection (Dolman 2019). Any particles in the air combine with water molecules during rainfall. This forms acid rain that can affect the solubility of limestone (Chen et al. 2022). In limestone weathering, precipitation is an important factor in providing the volume of acid rain needed for the weathering process to occur. On the other hand, the carbon cycle is the movement of carbon molecules in the atmosphere, land and oceans that has been embedded in the soil to form limestone (Dolman 2019). This cycle drives the disintegration and regeneration of limestone as carbon undergoes phase changes. Limestone captures carbon dioxide in the atmosphere to improve the health of the ecosystem (Kirchner et al. 2020). The cycle of plant growth and decomposition affects the biological process of limestone weathering. It is a form of biological weathering. Plant roots can crack the structure of limestone and the decomposition of leaves increases the acidity if it comes into contact with water (Wild, Gerrits, and Bonneville 2022). Consideration of these three different cycles, enable analysis to the formation and deterioration of limestone material.

This study aims to describe a method of design from the analysis of limestone material weathering to gain the value of limestone within the ecosystem as a water neutralizer and apply it in a circular design program. In its environment, natural limestone rock formations are an integral part for the maintenance of life and provide value. The design considers the role limestone has within the environment. It takes part in a circular scheme involving biogeochemical processes. This circularity can be affected by human influences in varying the speed or volume of elements transformed to the next phase of the cycle (Dontsova, Balogh-Brunstad, and Roux 2020). Allowing the weathering of limestone material and its application in a design program will improve the surrounding environment and maintain the life of ecosystems.

Methods

The study starts through observation and analysis of natural limestone rock formation material found in nature to understand the significance of weathering on the environment. The study analyses multiple sets of limestone rock formation in particular context, to analyse pattern of landscape and identify the aspects that take part in the weathering reaction. Tracing is done to highlight the form of limestone and investigate necessary surrounding elements to continue or discontinue the weathering process. Edges and boundaries of pattern existing in landscape are traced that show the border of the material. Any flows of water, living and decomposing vegetation are also traced from the photographs.

Based on the traces drawing, a diagram of the flows of reaction and relation to the water cycle, carbon cycle and plant growth and decomposition is made to show the connection of limestone material weathering with the wider ecosystem. Diagrams and cataloguing can help in processing the information obtained from tracing (Karimah and Atmodiwirjo 2021). The study also analyzes other spatial factors that affect the process of weathering such as limits, depth or living and non–living patterns to show how it can impact the reaction. A diagrammatic flow diagram showing the continuous and discontinuous processes will reveal the value of limestone material weathering towards the environment.

Based on reading on the impact of limestone weathering and the ecosystem, this study develops architectural programmatic scenario which employs the weathering mechanism of limestone material. The information of the value gained from limestone material weathering based on the analysis become the basis to programmatically optimize the improvement of the natural ecosystem in a context. The circular scenario and weathering operation are created to ensure the process of limestone weathering of limestone and the output of the process provide improvement to the life of the surrounding environment. In order to prevent the complete disintegration of limestone material in the context, coccolithophore algae is cultivated in the program. A weathered built environment that provides value towards the ecosystem is developed from the planned scenario.

Developing circular architecture driven by limestone weathering

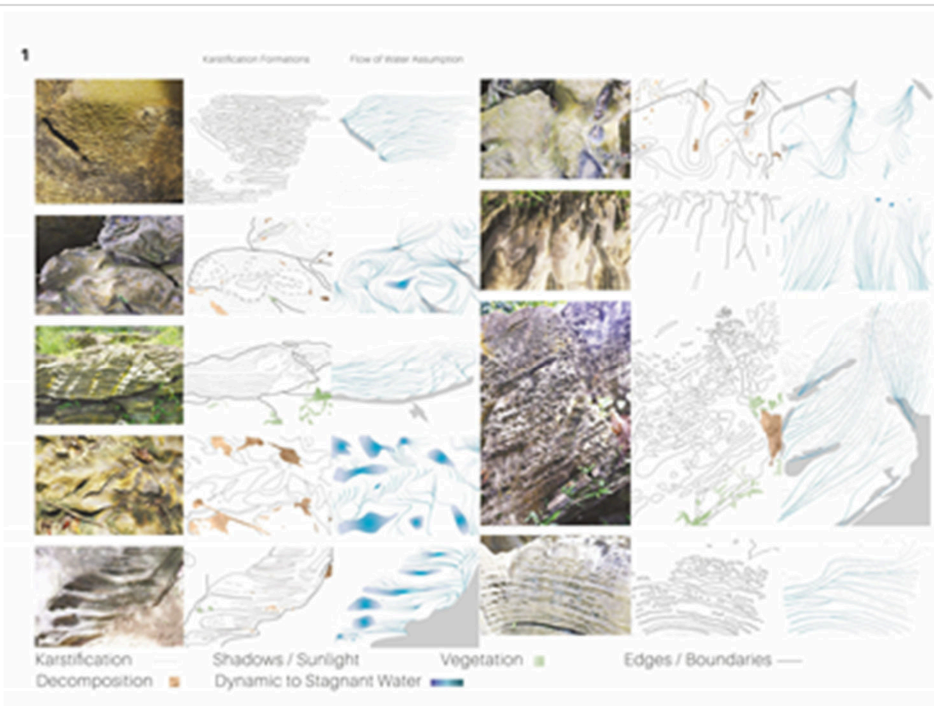
The forces and flows of nature form non–living structural material such as limestone. This study analyzes the process, forces and flows of nature in naturally occurring limestone that impact the process of weathering. The study focuses on limestone rock formations in Goa Garunggang, Sentul, West Java. Photographic documentations of limestone weathering are taken and analyzed spatially for any elements that contribute towards the limestone weathering. The interrelation of the elements and how it affects the weathering process is investigated.

Results and discussion

Pattern of landscape

The study traces weathering patterns on limestone material found in the photograph, which consist of edges of boundaries of the material, dynamic to stagnant flow of water, presence of living vegetation, decomposing leaves and direction of root growth. Tracing these elements provide understanding on the weathering pattern formation, growth and synthesis (Ball 2012). Weathering patterns on limestone material are projected through indentations and formations shaped by acid rain. Some photographs have bodies of water still present from previous acid rain precipitation. This weathering formation in limestone materials affects the flow of water as acid rain passes through. The boundaries or edges of the limestone material are drawn to highlight the limit of the weathering reaction as it occurs away from the rock. Tracing the gradient of dynamic to stagnant water enable identification of areas where water will flow at a faster rate or become stationary.

Any living vegetation present on the limestone material is outlined and noted for its proximity with other elements, such as stagnant bodies of water that is necessary for the growth of the vegetation. Decomposing leaves contribute towards weathering and its positioning is related to the pattern of the limestone weathering formation. The direction of root growth is also identified to analyze impact of biological weathering on the limestone material. Each element and its position within the limestone rock formation extend the process of weathering past the initial chemical weathering caused by acid rainfall. Figure 1 demonstrate different types of weathering on limestone and tracing of important elements that affect the process.



1. Chemical weathering of limestone.
2. Chemical and biological weathering of limestone.
3. Chemical, physical and biological weathering of limestone.

Figure 1. Tracing of photo documentation

The initial angle, thickness and shape of the edges of the limestone surface determine the overall weathering pattern (see figure 2). Horizontal, slanted and vertical limestone surfaces produce varying patterns of weathering and affect the amount of limestone dissolved. A horizontal limestone surface produces several indentations of water channels, leading to large areas where potential pooling of stagnant water can occur. The collection of water at the center of the limestone material increases the chances of growing living vegetation, leading to biological weathering.

Limestone with slanted surface directs the flow of water towards the limits or boundaries of the limestone surface. This reduces the amount of living vegetation that grows on the surface, as there is not enough supply of stationary water. Another possibility of positioning limestone surface is in vertical position, where water does not flow directly on the surface and is deflected by the vertical angle of the limestone. This creates weathering patterns with discontinuous channels or rounded indentations. There is no pathway created for the water to flow towards the edge of the material, leading towards the pooling and collection of water.

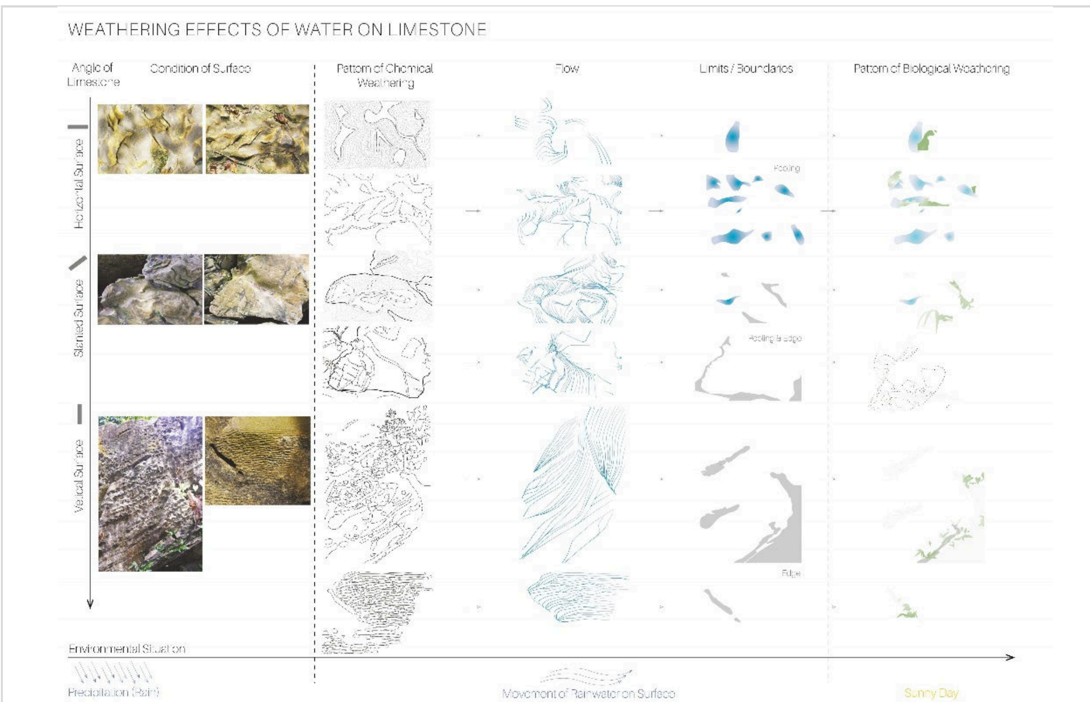


Figure 2. Factors affecting weathering of limestone

The difference in the surface angle of limestone affects the pattern of limestone weathering and the subsequent placement of the different elements. Leaves that fell are swept by the force of the water flow and are either pushed past the limit of the limestone material or stay in the stagnant indentation pools of water. Contact of water with the decaying leaves increases the acidity of water and rate of weathering (Yang et al. 2023). From the photograph documentations, it can be seen that a network of tree roots has taken formation on the surface of the limestone and extend themselves past the limestone material towards soil. The roots hold on to the limestone for support, potentially creating damage towards the structure of the material in the long term.

Two other factors that affect the limestone weathering process are the thickness and shape of the edge of the material. When depleted, thinner limestone material reveals the underlying soil where water will be absorbed and not collected for the growth of living vegetation. The edges shape of the limestone formation affects the weathering process and edge shapes that are irregular provide more potential points for the water to pass through. Water will travel downwards towards the ground and create indentation channels where it has passed more frequently.

By considering the incline, thickness and shape of edges of limestone material, placement of elements and patterns of indentations of the weathering process can be predetermined. These loosely predictable pattern configurations of a non– hierarchical order can be used as the basis of architectural scenario (Allen 2013). The spatial positioning of the elements and its self-formation according to the reaction of weathering is a naturally occurring process, that maintain the stability of life in the environment.

Identification of weathering cyclical process

The mechanism of weathering discussed in the previous section can happened following the three main cycles involved in the reaction (see figure 3). These processes take part interchangeably, causing disintegration or regeneration of the limestone material. Formation of limestone rock material in nature is explained by the carbon cycle. In a biological process, carbon dioxide in the atmosphere deposes into the seawater. Living marine corals, algae and plankton absorb carbon dioxide that then decomposes to form limestone on the sea floor through fossilization (Dolman 2019). The extraction and combustion of fossil fuel produce energy releasing carbon dioxide into the atmosphere through pollution. This continues the carbon cycle where atmospheric carbon dioxide is needed to form limestone.

The water cycle consists of the stages of precipitation, collection and evaporation. Water is an important resource that needs to be managed (Suryantini, Saginatari, and Yatmo 2022). Acid rain is formed when rainwater interacts with carbon dioxide, sulfur dioxide and nitrogen oxide in the atmosphere (Dolman 2019). When limestone is exposed to acid rain it causes dissolution of the material. Movement of water on limestone depends on the angle of the limestone. A vertical or slanted surface will cause the water to run off past the boundary edges of the limestone. If it is a horizontal or slanted surface, the water can collect on top of the material. The water will overflow and run off if the volume of water collected on the surface of the limestone has exceeded the capacity. Once the rain stops, the water evaporates. Water can also percolate past limestone since it is a porous material. The evaporation of water by sunlight transforms liquid water into vapor causing precipitation and repetition of the water cycle. The water cycle initiates the chemical weathering of limestone material. Acid rain deforms the limestone, creating indentations of water channels on the surface for water to run off or as an area for water collection.

The cycle of plant growth and decomposition explains the process of biological weathering that occurs on the material. It consists of sprouting, root extension, shedding and decay. The water collected on the surface of the material after precipitation becomes an ideal location for the growth of vegetation. Plants sprout and grow on the surface of limestone, as there is a stagnant source of water. Different types of plants were identified, such as moss and larger trees. These existence of plants causes biological weathering of the material as it causes the limestone to crack during the phase of root growth. If there is not enough water to sustain the vegetation it decays directly on the surface of the limestone. Trees growing above the limestone material also shed leaves on the material, creating decaying organic matter on limestone material which increases the acidity of water during precipitation. This contributes to further weathering process as more limestone particles dissolve into the water. Vegetation that has decayed fertilizes the surface of the material, improving conditions for new plants to sprout. The cycle of plant growth and decomposition goes on and further disintegrates the limestone material.

A continuous and discontinuous process specifies weathering mechanisms that allow other material reactions to occur. In the continuous processes, occurrences of collection, vegetation growth, shaded evaporation and root growth extend the impact of weathering. Discontinuous processes only happen for a shorter duration, when total run–off, overflow, percolation, complete evaporation, decay and disintegration stops weathering. Continuous processes ensure that the limestone maintains life as it can collect rainwater on its surface and plants and roots to grow. The discontinuous process ends weathering, when there is no water left on the surface. As shown in figure 4, the capability of limestone material to collect water naturally allows biological weathering to occur. It is a continuous flow of different types of weathering which accelerates the disintegration of limestone material. A discontinuous process slows down the effects of weathering. Constant disintegration of limestone will cause depletion in material.

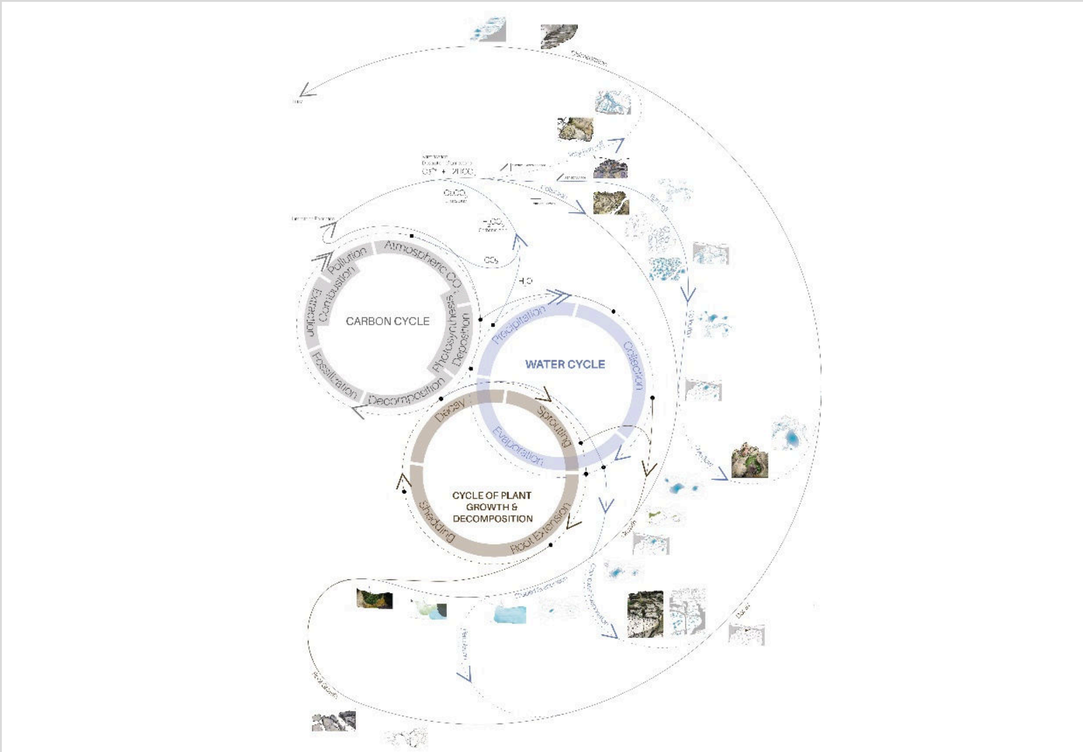


Figure 3. Cycles affecting weathering of limestone

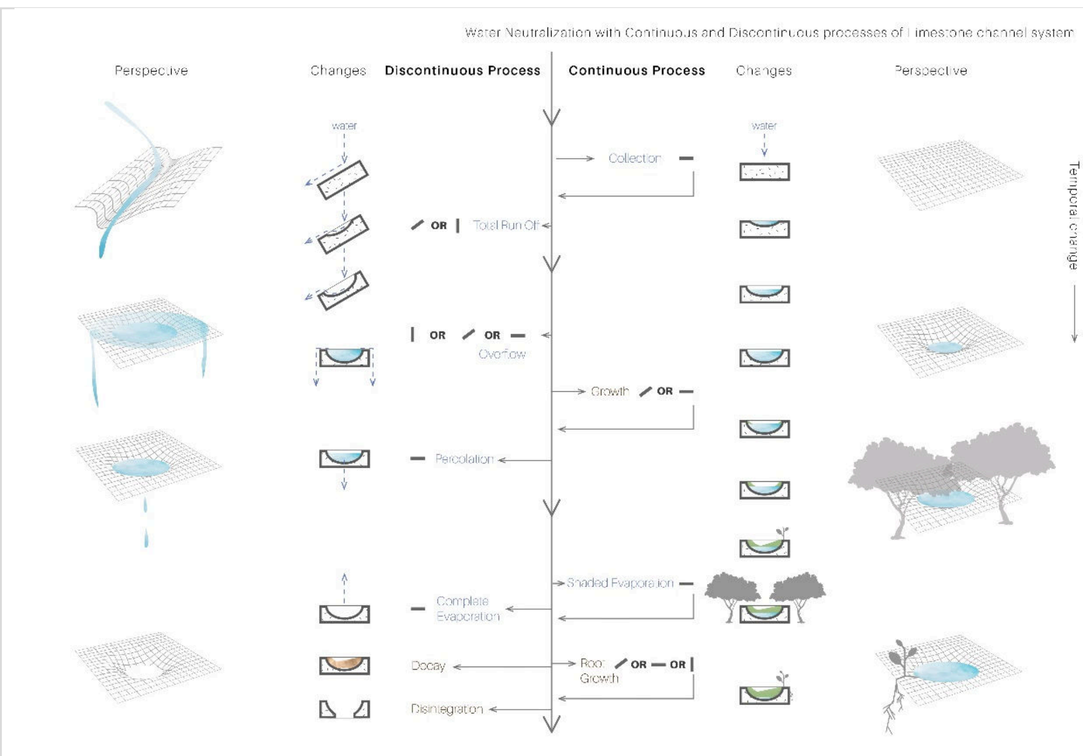


Figure 4. Continuous and discontinuous process of limestone weathering

Programming architecture based on weathering

The study proposes architecture based on weathering, creating space for reforestation and recreation driven by limestone material weathering. Diminishing presence of limestone material will make the acid rain difficult to be neutralized, and harming the environment in the long run. Maintaining a continuous process of weathering without depletion of limestone material is proposed to neutralize the pH of acid rain for the growth of vegetation. Discontinuous processes enable the overflow of rainwater, existing as a water filtration through percolation. Acid rain initiates the reaction and has different possible outputs. The water from the acid rain passes through limestone channels and become neutralized. It then flows directly to existing rivers, lakes or sea, collected by limestone material water basins or becomes filtered through percolation. The water that remains in the basin will be a source of water for the growth of vegetation in the surrounding area. Filtered water from the process of percolation is used for irrigation of plants and growth of Coccolithophore algae.

The study proposes architectural reforestation program that reintroduce the algae into the scenario to ensure that the limestone material will not be depleted (see figure 5). It can produce limestone by the reaction of dissolved carbon dioxide with calcium ions in the water. This removes more carbon dioxide from the atmosphere to be transformed into limestone (Moore 2021). The material produced by the coccolithophore algae can be distributed to maintain the thickness of the limestone channels or water basin (Bach et al. 2019). It promotes reforestation, recreation and regeneration of limestone material in the environment for the maintenance of life in the ecosystem.

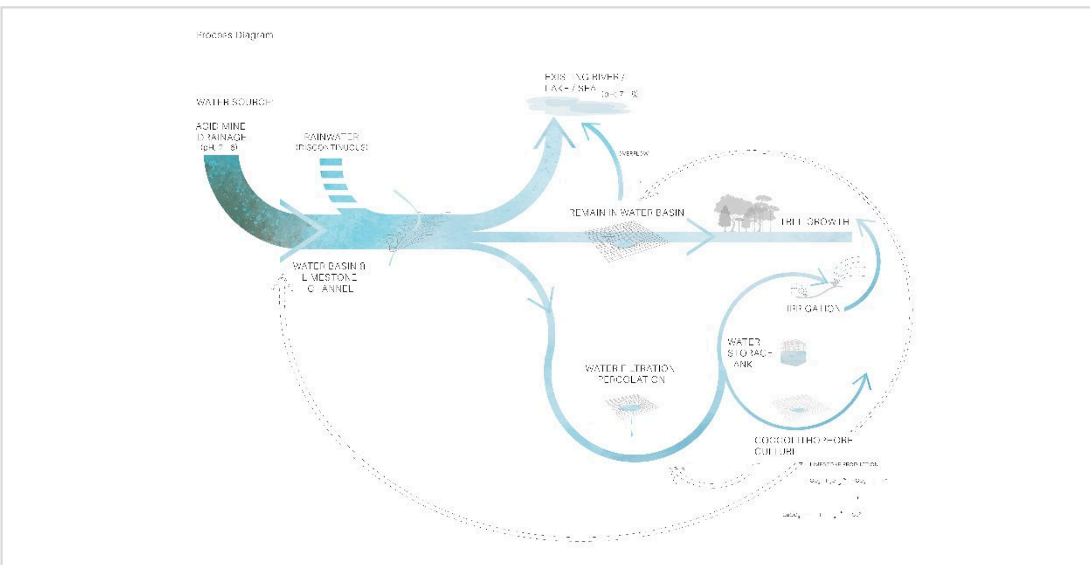


Figure 5. Proposed program

This proposed program is applied to an architectural design that is located in a former coal mine at PT. Bukit Asam Pit 1 Tanjung Enim, South Sumatra (Resman et al. 2018; Putri, Pitulima, and Mardiah 2019). Due to previous mining activities, run off water from the soil needs to be treated before it pollutes natural streams (Mulopo 2022). The design depicted in figure 6 implements a water neutralization process of acid mine drainage by capturing the run off water from the land to pass through limestone channels. Several basins lined with limestone can hold the run off water while the remaining flows along the limestone channels towards existing streams. The water basins also act as a shelter for the overflow of run off water to be redirected towards the channel (see figure 7). Run off water is also passed through a water percolation system consisting of limestone slab and soil. This filtered water is stored in a water tank for the culture of coccolithophore algae to replenish the weathered limestone. People passing through the site will gather to learn about the water neutralization process and rehabilitation of the landscape. Water is distributed evenly in the landscape for reforestation and as a visitor recreation area.

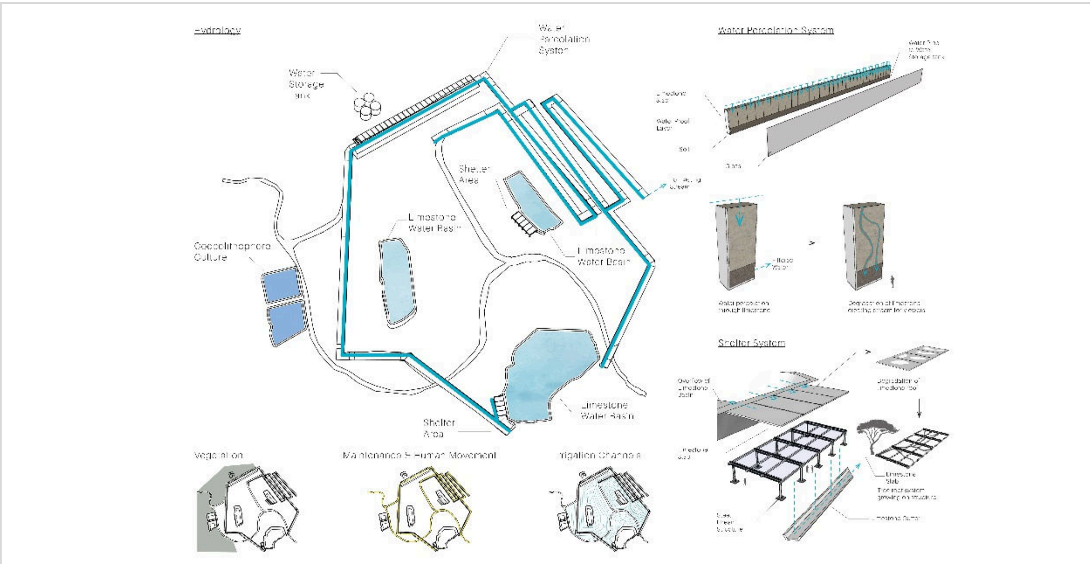


Figure 6. System of limestone water neutralization

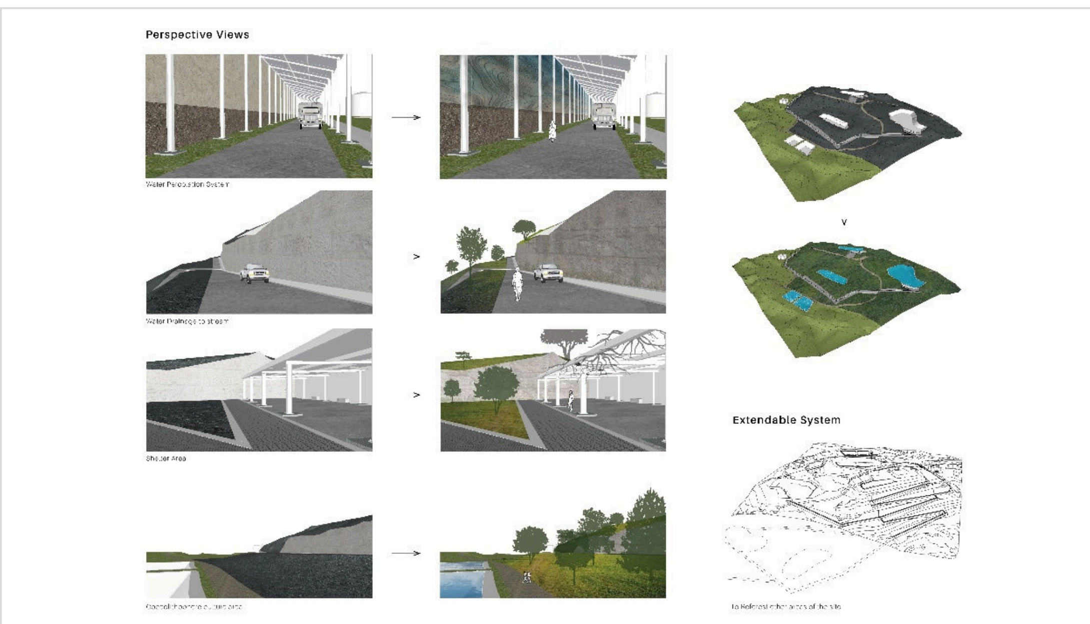


Figure 7. Perspective views of design on site of former coal mine throughout time

Conclusions

This study analyzes limestone-weathering formation as the basis of circular architectural design. It reveals that limestone presence generates particular values for the environment quality, by creating neutralization of acid rain, enabling water filtration through percolation, and reducing atmospheric carbon dioxide. The study proposes to address how limestone weathering can be implemented into an architectural program that follows continuous and discontinuous processes. A spatial understanding of limestone material in the environment provided the information necessary to organize the reaction of weathering in different forms of chemical and biological weathering. The incline, thickness and edge shape of limestone material determines whether the weathering process happen in a continuous or discontinuous way. By creating an architectural proposal that ensures the existence of limestone in the environment, the growth of vegetation and life can be promoted and maintained.

Exploring architecture that allow weathering to happen in nature, instead of prohibiting them enable the effects of weathering to create value towards the surroundings ecosystem. Investigating the limestone weathering shows that it is an important natural process that should be fostered. Such process of weathering provides benefits towards the context, by aiding in the growth of living vegetation, water purification, and acidic rain neutralization. The study utilizes this process of weathering for reforestation and recovery of a mining site to be used for recreational proposes. Application on the weathering as a way to restore the quality of the environment demonstrate a circular design process that does not only rearranges the material flow in the environment, but appropriate natural process to produce certain qualities of the environment itself. Other processes that can be researched further from this study are the production of limestone from coccolithophore algae to ensure the limestone resource is not depleted. More analysis for the feasibility of the proposed program and its application into the programmatic context of architecture potentially provide other contribution for architecture driven by the processes happening in nature.

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Author(s) contribution

Astrid Vidya Primadhani contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Kristanti Dewi Paramita contributed to the research. concepts preparation and literature reviews,
data analysis, of article drafts preparation and validation.

Yandi Andri Yatmo contribute to methodology, supervision, and validation.