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### INTRODUCTION

With the letter dated from the first of August 2022, the THP Engineering SRL has been awarded for the research study "Consultancy service involving an assessment of stocks and extraction/ production potentials of alternative sources of sand and alternatives to sand (Lot 1A)". The aim of the assignment is to assess the potential of sustainable alternatives to river sand to meet the growing demand for road construction, building construction and landfills in the Vietnamese Mekong Delta region and Ho Chi Minh City (HCMC). The findings generated from this assessment will be used to advocate for a change in sourcing practices in the construction sector and in relevant policies, rendering the credibility of the study in the eyes of stakeholders from the construction sector and government particularly important. While the actual findings need to be presented in a concise manner and a language understandable to professionals who are not experts in material sciences or civil engineering, the sources and methodology used need to be documented in a transparent and comprehensive manner, and the findings have to be based on scientific methods and literature, which should be peer reviewed as far as possible.

# THE SPECIFIC TASKS WHICH WERE IDENTIFIED TO BE UNDERTAKEN ARE AS FOLLOWS

Alternatives to be considered include natural aggregates outside active riverbeds, like sand pits and crushed sand (m-sand) and artificial aggregates, like recycled aggregates or other substitutes that:

- a. Have been proven (at least at lab scale) to be technically suitable substitutes for sand for different purposes in the construction sector (concrete-quality, land reclamation and other uses such as cover or drainage layers in landfills).
- b. Can be exploited and/or produced with limited and mitigable negative social and ecological impacts,

c. are available in stocks that are large enough to be of interest to construction companies.

### ACCORDING TO THE TENDER, THE ASSIGNMENT SHOULD INCLUDE

- A desk review to produce a preliminary list of potential alternative sources to replace river sand in road construction, building construction and landfills based on their technical suitability/applicability in the construction sector.
- A structured assessment of the comparative sustainability performance of the potential alternatives, based on an internationally recognised method or tool (e.g. Life-Cycle Analysis, Multi-Criteria Analysis).

# CURRENT PROJECTS RELEVANT TO THIS ASSIGNMENT

"Drifting Sand: Mitigating the impacts of climate change in the Mekong Delta through public and private sector engagement in the sand industry"

With financial support from the German Government, the World Wide Fund for Nature (WWF) is working with national and provincial stakeholders to mitigate the Mekong delta's vulnerability to climate change through an improved management of sand resources.

Under the project, the WWF will:

- a. Establish a delta-wide sand-budget in consultation with stakeholders to create a uniformly agreed understanding of the scope and impact of unsustainable extraction rates;
- Promote public awareness of the impact of unsustainable sand exploitation in the Mekong Delta;

- c. Promote the participation of, and dialogue between, key actors in the Vietnamese construction sector and provide information on the risks associated with sand mining and opportunities of sustainable alternative sourcing for sand;
- d. Develop and propose improved policies and practices in relation to sustainable sand mining.

The project is implemented by WWF-Viet Nam and WWF's regional hub for the Greater Mekong region, in collaboration with WWF Germany. This assignment will contribute to the Drifting Sand project works on sand sourcing investigations in order to develop responsible sand and mineral management policies.

## "SAND!—Alternative Sand Production and Risk Reduction of Dredging in Vietnam" (duration 05/2019–04/2023)

The German-Vietnamese project SAND!, cofinanced by the Federal Ministry of Education and Research, developed technological and management-based methods for reducing the environmental impact of dredging in the Mekong Delta and generating alternative building material resources.

The project contributes to sustainable development in Vietnam by improving sediment management in the Mekong River and related

aspects of sustainable resource, land and water management, including flood prevention.

The objectives of the project were the following:

- (1) Development of measures for the reduction of the environmental impact of the sediment dredging activities in Vietnamese rivers and the process optimisation for ongoing dredging activities
- (2) Development of alternatives for sand production, including a raw assessment of available primary and secondary raw materials
- (3) Development of a regulatory framework for the future use of mineral substitute building materials and crushed sands from hard rock, including quality assurance requirements for use as alternative building materials.

Efforts have been made to link the outcomes of the SAND! Project to the Drifting Sands project in order to make the data available in a compact form. To do so, all collected, measured and modelled data from the SAND! Project have been re-assessed in terms of their usability in the Drifting Sands project. However, due to COVID-19 restrictions during the project period, the project focus was placed more on secondary materials than on primary materials. Anyhow, all information on primary raw materials is needed to be clarified and verified with the competent authority.





# DESCRIPTION OF THE CURRENT SITUATION

Sand is one of the world's most consumed natural resources after water (Dan Gavriletea, 2017). It forms the unrecognised building block of economies due to its ubiquitous and versatile application in various sectors such as construction, industrial production like glass, electronics, cosmetics, paints, shale gas etc. Different types of industrial applications are made according to the specific properties of different sand types. The construction industry is the major consumer of sand, which in turn is fuelled by an insatiable demand for concrete caused by rapid urbanisation across the globe, primarily in developing economies (Bide et al., 2020). Sand can be acquired cheaply and easily, thus making it the largest mined and traded resource by volume. At the same time, there is low awareness of the widespread impacts from extraction in the sand extraction sector even the topic is regulated under consideration of the CBD and UNCLOS but in many countries the regulations are not enforced. Some countries have more strong regulations, for instance South Africa

(Green, 2012) and Italy (here regulated through nature protection zones, Koehnken et al. 2020), according to the UN Environment Programme, global sand extraction is currently at around 50 billion tons a year (roughly half of overall nonmetallic minerals), in order to meet the soaring demand for construction and land reclamation (UNEP and GRID, 2019).

Sand extraction is always localised, at preferred common quarry sources such as riverbeds, flood plains, lakes, beaches and oceans. Not all types of sand are preferred for construction activities, a proper gradation of particles from 150 microns to 4.75 mm is primarily required (Padmalal and Maya, 2014a). For this reason, sand from water bodies is preferred for its naturally sorted grain size and angular shape imparted from the fluvial process, thus eliminating the cost required for processing such as mining, grinding, and sorting for appropriate size distribution.

Figure 1: Global resource extraction in four categories (biomass, fossil fuels, metal ores and non-metallic minerals) 2010-2050 (source: Schandl et al., 2018)

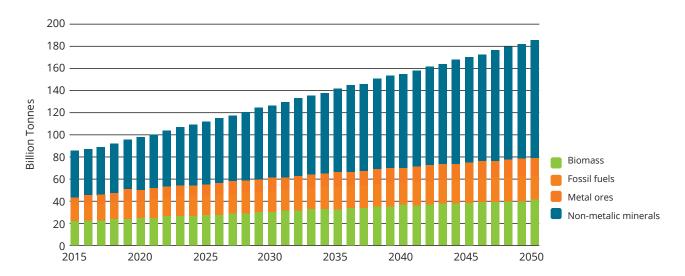


Figure 2: Different sand sources across world (Padmalal and Maya, 2014b)

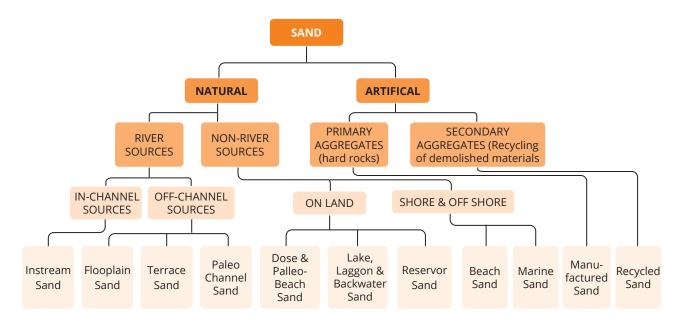
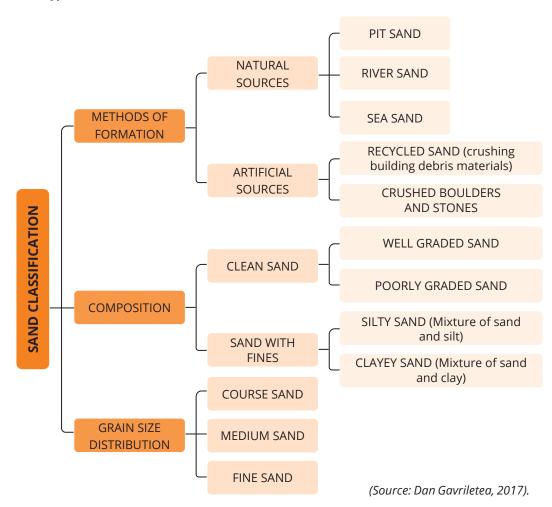


Figure 3: Various types of sand classification (source: Dan Gavriletea, 2017)



This imbalance between demand and supply has not received enough attention because of the easy availability of sand. Negatively affected by unsustainable exploration are rivers, dikes and stone embankments leading to a series of adverse environmental and social implications (UNEP, 2014). The extraction rate of sand is manifold greater than the rate of natural renewal of sand by rivers (UNEP, 2014). An irreversible impact occurs from bed form degradation, change in water depth, sediment characteristics, water quality and quantity, biological and coastal environment, socioeconomic environment, damage to infrastructure, riverbank erosion, salt intrusion in agriculture, fish population and vegetation loss (Padmalal and Maya, 2014c). The Asia-Pacific region faces a serious sand mining issue along with a huge sand demand for development projects. In 2017, the sand price quadrupled within one year in Vietnam and it was predicted that the country would run out of the easily available sand resource by 2020 (Dinh, 2020), a prognosis that has proven to be true.

The Vietnamese Mekong Delta (VMD) region is roughly a 40,000 square kilometre (km²) triangle stretching from Gò Công in the east to Tân Châu and Hà Tiên in the northwest, down to Cà Mau at the southern tip of Vietnam, including the islands of Phú Quốc and Côn Đảo. The VMD is divided into two regions: an inner delta that is dominated by fluvial processes, and an outer delta that is affected by marine processes. The VMD, together with the Dong Nai River basin, builds a large coalescent delta that covers an area of >50,000 km<sup>2</sup> and is home to about 30 million people including HCMC, Vietnam's largest city. The construction of hydropower dams and the extraction of sediments for a booming construction sector have already reduced sediment transport to the delta by about 77% between 1992 (160 Mt) and 2014 (75 Mt) (Le Manh Hung, 2014). Regarding sand mining specifically, excessive extraction concessions, illegal sand mining and a lack of awareness have resulted in extraction rates far beyond the replenishment capacity of the Mekong River (Le Manh Hung, 2014). Especially along the Mekong's main tributary branches, the consequences have become increasingly apparent, exposing millions of riparians to riverbank erosion, saltwater intrusion and higher tidal amplitudes (Tuoi Tre News, 2017).

Due to the lack of other sediment resources, sand has thus far only been extracted from rivers by dredging and pumping in Vietnam. This has led to

enormous environmental impacts in recent years, including the sharp increase in the flood risk due to the changed hydromorphological structure of rivers, which a) results in a higher flow velocity and thus an increased risk of riverbed erosion, and b) to massive geotechnical problems in relation to the river slope and bank stability and thus the infrastructure in proximity to the rivers (Ahmed et al. 2020). For this reason, there are sections of rivers in which sand extraction has already been completely banned (Ahmed et al. 2020).. The situation has led to a four or fivefold increase in building-sand prices. Several provincial construction departments have already announced that public construction projects have become more expensive and delayed due to the lack of sand (Ahmed et al. 2020).. Sand prices are rising continuously throughout Vietnam, with the Mekong Delta and Ho Chi Minh City being particularly hard hit due to the economic situation (Ahmed et al. 2020).. In principle, however, this problem exists in all of Vietnam's larger catchment areas, as the country has no natural sand deposits other than river sand due to the geological conditions.

A report presented by the government in August 2017 by the Department of Construction Materials in the Viet Nam Ministry of Construction, based on statistics from 49 provinces and cities, indicated that permits had been issued for the extraction of 691 million cubic meters of sand by the end of 2016 (Bacninh.gov, 2017). According to the data from the Ministry of Construction in Vietnam, the domestic demand for construction sand was estimated at around 2.1-2.3 billion m<sup>3</sup> between 2016 and 2020, while the country's total sand reserves are only slightly more than 2 billion m³ (Tuoi Tre, 2017). While sand extraction in Vietnam was 55 million cubic meters in 2011, the production volume of sand in Vietnam reached around 34.8 million cubic meters in 2021 (statistics based on Minh-Ngoc Nguyen, 2022). At this rate of sand consumption in Vietnam, the country will soon run out of sand as a building material. A bathymetric study of a branch of the Mekongthe Tien River- estimated sand extraction to be at a rate of 4.64 ± 0.31 million m<sup>3</sup>/year over a 20 km length, highlighting an unsustainable practice and also indicating insufficient sediment supply from the upper reaches of the river (Jordan et al., 2019). Massive sand extraction has been identified as an important driver of changes in Mekong sediment dynamics (Bravard et al., 2013; Brunier et al., 2014). In a pilot stretch of the river, Brunier et al. (2014) found that dredging led to

riverbed subsidence rates of around 0.5 m/year and an increase in drag stresses of around 0.25 N/m². These developments point to increased, long-term erosion in the Mekong River, which can also lead to increased bank erosion.

However, this is only one aspect of the problem. Scientists from the Institute for Climate Change at the University of Can Tho recently pointed out that the unbridled dredging for sand extraction has already created deep holes in the Mekong River and is the reason for massive subsidence in the Mekong Delta. The Mekong Delta loses around 500 hectares of land every year due to subsidence and riverbank erosion, and due to this hundreds of families lose their houses and fields (Worldbank, 2021). It was also pointed out that, in the near future, when all 11 dams on the Upper Mekong are completed, there will be no more alluvial sediment transport in the delta. If dredging continues at the sites in operation and further mining sites are developed, 1/3 of the Mekong Delta will disappear before 2050, which will have irreversible environmental impacts in terms of flood risk, subsidence and biodiversity (Ahmed et al., 2020). The overexploitation has negative consequences, especially for the environment and people in the areas where sand is extracted. In the Mekong Delta and other coastal areas of Southeast Asia, the extraction of sand is already causing a shortage of groundwater and subsidence. As a result, seawater penetrates further and further inland creating salty drinking water, fields and soils.

Sand mining is also a common cause of shore and coastline erosion, making these areas more prone to natural disasters such as floods, storm surges or tsunamis. A large proportion of the sand that is extracted from VMD is required as construction material for HCMC. In this regard, the aim of the assignment is to assess the potential of more sustainable, financially competitive alternatives to river sand and to provide a multi criteria assessment for the alternative aggregate sources from a micro- and macro-economic perspective.

The results of the assignment will contribute to the implementation of the Government Decree 09/2021/ND-CP of 9 February 2021 on the management of building materials, and Prime ministry Decision 1266/TTg-QĐ dated 18 August 2020 on Strategy for the development of building materials in Vietnam for the period 2021 to 2030 with a concept to 2050. The decree 09/2021/ND-CP specifies the management of the development, production of, and use of building materials in construction work to ensure safety, efficiency, sustainable development, environmental protection and resource conservation. The strategy for the development of building materials in Vietnam for the period 2021 to 2030 with a vision to 2050 with the following content:

- a. Build an efficient and sustainable building materials industry, which essentially meets domestic demand, gradually increases exports and contributes to socio-economic growth and development;
- Apply scientific, technological and managerial achievements, especially [relating to] the Fourth Industrial Revolution;
- Minimise the environmental impact of the extraction and processing of minerals for building materials and the manufacture of building materials;
- d. Promote and encourage all sectors of the economy to invest in, and develop, the building materials industry;
- e. Distribute the network of building material production sites nationwide according to the natural and social conditions of each region;
- f. Use natural resources efficiently, and thoroughly save energy, raw materials and fuel.
- g. Minimise impact on the environment during the mining, processing and production of construction materials

In the annex of that document, the following goals are established (excerpt):

#### 1. PERIOD 2021-2030

#### CEMENT

- Only invest in a new cement clinker production plant with a capacity of not less than 5,000 tons of clinker/day, associated with the raw material area and invest in a power generation system that takes advantage of exhaust heat, fully satisfying enough indicators on technology and environment.
- By 2025, cement plants with a capacity of less than 2,500 tons of clinker/day, consuming a great amount of raw materials, fuel and energy, must invest deeply in technological innovation to improve productivity and product quality, energy saving and environmental protection.
- Invest in cement grinding stations with suitable capacity in areas unfavourable for raw materials to produce cement clinker.
- Average rate of clinker use in cement production is 65% for the whole industry; 35% minimum use of cement additives.
- Total designed capacity of cement plants by 2025 must not exceed 125 million tons/year; and by 2030 will not exceed 150 million tons/year.
- By the end of 2025, 100% of cement production lines with a capacity of 2,500 tons of clinker/ day or more must install and operate power generation systems that utilise exhaust heat.
- By 2025, to use at least 20%; by 2030, use at least 30% of thermal power fly ash or other industrial waste as substitute materials in clinker production and as an additive in cement production.
- Export restrictions, clinker and cement export rates do not exceed 30% of the total design capacity.

#### 2. PERIOD 2031-2050

#### CEMENT

- Maximum average rate of using clinker in cement production is 60% for the entire industry; at least 40% of admixtures for cement use.
- Production technology has a high degree of automation, thoroughly applying information technology to management, production and business activities.
- At least 60% of production lines use thermal power fly ash or other industrial waste to replace clay materials in the production of clinker.
- Using over 30% fly ash, thermal power slag or other industrial waste as an additive in cement production.
- Using alternative fuel up to 30% of the total fuel used to produce cement clinker by the treatment and use of domestic waste and agricultural and industrial waste.

#### 1. PERIOD 2021-2030

#### **CONSTRUCTION SAND**

- Invest in and develop establishments exploiting and processing natural sand and producing artificial sand to fully meet the domestic construction demand.
- Encourage investment in research and technology transfer in the production of crushed sand, sea sand, saltwater sand, brackish water sand, fine sand into sand qualified for use in concrete and mortar.
- For natural extraction: Use advanced mining technology in combination with cleaning to remove impurities to improve sand quality. Waste generated during the treatment process must be collected, stored properly or reused.
- For crushed sand: The technological line of crushed sand production must be advanced and synchronous (including processing, screening, sorting, and environmental treatment equipment and other equipment).
- Use natural resources of of minerals, fuels and energy; efficiently and economically; use industrial and construction wastes for construction sand production.
- Gradually limit the use of river sand as backfilling materials.
- Ban the use of river sand meeting the technical standards for concrete to use as landfill materials in construction. Do not export natural construction sand.
- Strengthen the development of artificial sand products to meet demand; strive to achieve the target of using crushed sand, recycled sand from industrial and construction wastes to replace at least 40% of the use of natural sand in construction.
- Step up the production and use of brackish water, fine sand and sea sand together with technical solutions, striving to achieve the target of using them as a substitute for 10% of the natural sand used in construction.

#### 2. PERIOD OF 2031-2050

• Minimise the use of natural sand in construction and raise the rate of using crushed sand and recycled sand from industrial and construction waste, and brackish water sand to at least 60% of the total amount of sand used in construction.

The unavailability or shortage and high cost of river sand or other fine aggregates will affect the construction industry greatly (Kala et. Al., 2020). Due to this, several research projects were undertaken for easy and cheaply available alternative materials to replace sand completely or partially. The research trend follows a circular economy approach, involving waste generated during industrial, mining, domestic and agricultural activities as well as industrial byproducts. These products can have a major use in construction applications, while at the same time reducing the disposal problems associated with these waste streams and cost reduction of

building materials (Madurwar et al., 2013). One well-understood and widely applied alternative to river sand is 'crushed' or 'manufactured (m)-sand', which involves processed aggregates under the size distribution of river sand using confined process machines. In developing countries, the application of M-Sand involves problems in lack of required quality, which causes limitation in its use. Currently green infrastructure developments require these types of alternative materials to satisfy the strict physical property standards and the resources need to fulfil certain quality standards and to be available locally in order to be economical (Sankh et al., 2014).



# APPROACH AND METHODOLOGY

The expected result of this assignment is a detailed description of alternative sand sources other than river sand available in the 13 Vietnamese Mekong Delta provinces and HCMC that can be exploited without major environmental damage to (inter alia) climate resilience, ecosystems and biodiversity of the delta activities. This should cover:

- A desk review to produce a preliminary list of potential alternative sources to replace river sand in road construction, building construction and landfills based on their technical suitability/applicability in the construction sector.
- Astructuredassessmentofthecomparative sustainability performance of the potential alternatives, based on an internationally recognized method or tool (e.g., Life-Cycle Analysis, Multi-Criteria Analysis).

Details of this approach and methodology are given below.

A desk review to produce a preliminary list of potential alternative sources to replace river sand in road construction, building construction and landfills based on their technical suitability/applicability in the construction sector.

The first step of the desk review was the identification of the evaluation criteria and the selection of material options. The main activity was therefore the analysis of the existing construction norms to identify the requirements for building materials in Vietnam, particularly for concrete, road construction and landfill engineering. After this set of material requirements had been established, the search for building material alternatives was undertaken. In this regard, it had to be taken into consideration that due to the price of building materials as a mass resource, this material can usually not be transported any great distance and still remain an economically feasible building material. The typical distance that was assessed for Vietnam in the MAREX project is around 30 km.



However, rising prices might lead to a transport distance of up to 100 km.

The desk review comprised the following working steps:

- Literature review
- Review of projects dealing with the topic of sand scarcity
- Internet search, database research (particularly Vietnam biomass atlas)
- Remote data research
- Summary of the collected data

Generally, the screening activities focused on two types of material to replace sand: Primary raw materials and secondary raw materials

From the original list of identified materials, only those with a certain minimum material flow were investigated in detail. They were assessed in terms of:

- exploitability of the identified stocks of alternative aggregate sources given currently available technologies (with a particular focus on those existing in Vietnam),
- technical suitability and financial viability,

 suitability for construction purposes, standards and availability.

All collected data is documented in this report and a structured assessment of the comparative sustainability performance is presented.

## Structured assessment of the comparative sustainability performance of potential alternatives, based on an internationally recognised method or tool.

The main objective was to estimate the environmental footprint of different sand alternatives utilised in selective construction applications replacing conventional materials. In the present study Life-Cycle Analysis (LCA) was used as a comparative sustainability performance tool. LCA is the most widely used holistic methodology, a multi-stage process, the detailed definition of which is given in the international standards of the series ISO 14040 and ISO 14043 (DIN 14040/14043). According to ISO 14040, LCA is defined as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). The UNEP/SETAC Life Cycle Initiative defines LCA as "a technique that is used to assess the environmental aspects associated with a product over its life cycle" (UNEP/SETAC, 2011).

The combination of individual processes (unit processes) that form a product's life cycle is called the "product system" (Guinee, 2002). LCA aims to evaluate the environmental burdens of a product or a process. Thus, it can be applied for a variety of purposes, including identifying the source of environmental impacts associated with a product, comparison of similar products, or the design of new products, etc. Other major applications of LCA concerning products include green purchasing, eco-labelling and eco (green)design (Guinee, 2002). LCA studies can also be used in support of complex business strategies and decision-making, government policies or sector-level initiatives. LCA serves the purpose of expressing the potential environmental impacts and damages associated with a product or service system in a way supporting comparisons between alternatives, both at the level of the individual substance emission and at the level of the entire studied system (UNEP and Life Cycle Initiative, 2019).



LCA has a structured four-stage framework:

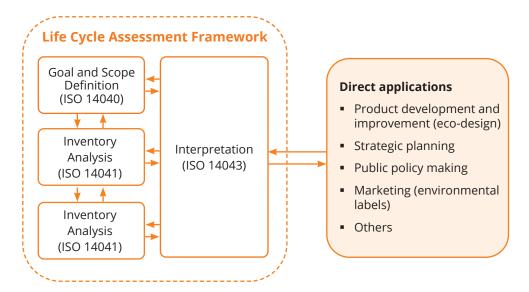
- goal and scope definition,
- life cycle inventory,
- life cycle impact assessment,
- interpretation

The LCA methodology is also recognised in Vietnam through the following norms:

- TVCN ISO 14040:2009: Environmental management-Product lifecycle assessment, principles and framework
- TVCN ISO 14041:2011: Life Cycle Assessment of Products-Principles and Framework
- TVCN ISO/TR 14047:2018: Environmental Management-Life Cycle Assessment-Illustrative examples of the application of ISO 14044 to impact assessments
- TVCN ISO/TR 14048:2012: Environmental Management-Life Cycle Assessment-Data Documentation Format

LCA is a tool for quantifying the environmental performance of products taking into account the complete life cycle, starting from the production of raw materials to the final disposal of the products, including material recycling if required. LCA is especially effective in comparisons of products, e.g., building materials that differ in their raw materials composition but have the same functionality (Marinković et al., 2010). In such cases, LCA can serve as a basis for decision-making to improve sustainability in the construction industry (Turk et al., 2015). The general LCA approach can be seen from the following figure.

Figure 4: General approach to Life Cycle Assessment



#### **GOAL AND SCOPE DEFINITION**

The determination of the goal and scope of the investigation is decisive for the result of a study. The benefit and function of the product to be examined and its life cycle must be defined. Assumptions and the limitations of the study are noted. The so-called "functional unit" is also to be defined, i.e., the product-specific variable to which the environmental impacts are subsequently related. Examples are 1kg of material, 1kWh of electrical energy, 1ha of agricultural land, etc.

#### LIFE CYCLE INVENTORY

The life cycle inventory makes quantitative statements about the consumption of raw materials and the emission of pollutants into the environment along the entire life cycle. Due to the selection of the examined emissions, the previously defined system boundaries and the selected allocation rules, the descriptive life cycle inventory analysis is not free of judgments. Allocation means assigning the environmental impact to the various output variables for byproducts (e.g., wheat and straw). The creation of the life cycle inventory is supported by various databases such as Ecoinvent.

#### **LIFE CYCLE IMPACT ASSESSMENT**

The impact assessment assigns the results of the life cycle inventory analysis to various impact categories according to scientifically based criteria. An impact category summarises the environmental impact of the individual substances on an environmental issue such as global warming, nutrient enrichment or summer smog. The importance of the individual emissions for the respective impact category is determined using impact factors. For example, nitrous oxide contributes 298 times more to global warming compared to CO2. The impact assessment can be carried out with a selection of impact categories (so-called "midpoints") or the impact on protected goods/protection goals, so-called "endpoints" (e.g., human health, ecosystem quality, natural resources) can be modelled. A full aggregation of the environmental impacts is achieved by weighting the endpoints.

#### INTERPRETATION

In the evaluation and interpretation, all previous steps are critically examined and the parameters that are essential for the result are identified. The consistency and completeness of the investigation is checked, and a sensitivity analysis provides information about the uncertainty range of the results. The indicators of various alternative products and respective processes can be compared with each other. Recommendations are derived according to the set goals or an ecological

performance is proven (e.g., the reduction of greenhouse gas emissions). LCA supplements the sectoral approaches in environmental protection such as air pollution control, water protection, soil protection, etc.

The life cycle assessment will be carried out using the "Ecoinvent 3.6" database and the software "Simapro 9.2". The software provides a user interface, the environmental information from the Ecoinvent database, and the options for the impact assessment method. Simapro software was developed by PRé Sustainability. Professional versions are available as a single user or a unique multi-user network version, which is ideal for teamwork. Educational versions come in three types for education purposes only. For paid research and consultancy type projects, the professional version is usually most appropriate.

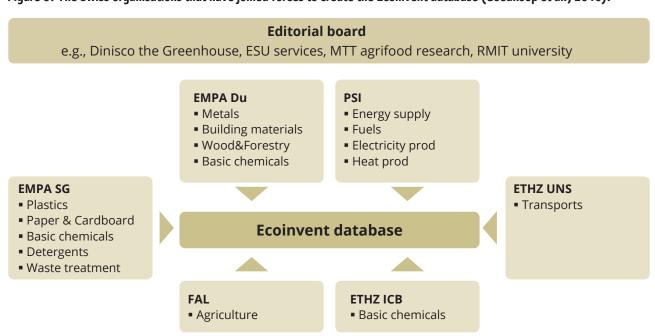
SimaPro allows the modelling of products and systems from a life cycle perspective. Users build complex models in a systematic and transparent way using SimaPro's unique features, such as parameters and Monte Carlo analysis. SimaPro comes fully integrated with the well-known Ecoinvent database and is used for a variety of applications, like:

- Carbon footprint calculation
- Product design and eco-design
- Environmental Product Declarations (EPD)
- Environmental impact of products or services
- Environmental reporting (GRI)
- Determination of key performance indicators

SimaPro comes with the Ecoinvent database, which covers over 10,000 processes. This database is the result of a joint effort by various Swiss institutions to update and integrate several life cycle inventory databases. The ETH Zurich, PSI, EMPA, EPF Lausanne and ART provide data for the Ecoinvent database. A group of LCI experts from these institutions are responsible for data collection. Additionally, there is an "editorial board" which is responsible for quality control. It performs the review, validation and editing of all new datasets before their inclusion in the Ecoinvent LCI database under the supervision of the LCI experts.

The software used is not open-source. Open-source options like openLCA as model and GEMIS as data base are available. However, both have fewer functionalities and the data base has fewer data sets. ProBas is also a free data base, however, it does not reach the content quality of Ecoinvent. For this reason, SimaPro was selected as a model and Ecoinvent as a data base.

Figure 5: The Swiss organisations that have joined forces to create the Ecoinvent database (Goedkoop et al., 2016).



The Ecoinvent database is extensively described on the Ecoinvent website: www.ecoinvent.org. You can register as a guest to see the metadata. Below is a summary of the key characteristics of the Ecoinvent database (Goedkoop et al., 2016):

- Covers a broad range of data.
- Consistent application of system boundaries and allocation.
- Well documented; the extensive Ecoinvent background reports can be accessed via the SimaPro help menu, the Ecoinvent website or the Ecoinvent CD.
- Consistent specification of uncertainty data, usually as a lognormal distribution with standard deviation.
- Emissions are specified with subcompartments, for example an emission to air can be specified as an emission in a high or low-density population area or stratosphere. Impact assessment methods can differentiate between these specifications.
- Includes capital goods as a default, which is important for energy systems such as wind and hydropower, but also for transportation systems.
- Comes in the EcoSpold 2 format which has become a de-facto standard that is very (but not completely) in line with the ISO 14048 standard.
- Is updated regularly by the Ecoinvent centre.

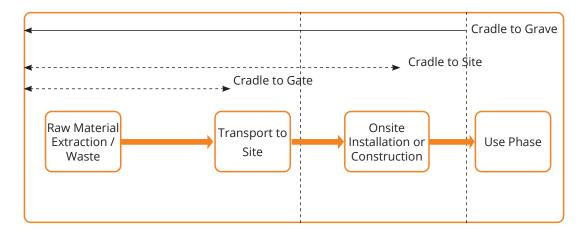
This database is a rich resource which, in most cases, satisfies all background data requirements. Version 3 of the Ecoinvent database has a more international scope (Goedkoop et al., 2016).

In the results report, information and results are provided for:

- LCA on Road Subbase Layers Utilising Alternative and Waste Materials
- LCA on Landfill Capping Layers Utilising Alternative and Waste Materials
- LCA on Non-Reinforced Concrete C25/30 Using Alternative Cement Replacement
- LCA on Non-Reinforced Concrete C25/30
   Using Different Aggregates

For each assessment subject the respective functional unit was defined. The definition of a Functional Unit (FU) is essential for building and modelling a product system in LCA. A FU is a quantified description of the function of a product that serves as the reference basis for all calculations regarding impact assessment. The FU of a product system is a quantified description of the performance requirements that the product system fulfils. In this LCA analysis, only the production stage involved in the supply of raw materials and alternative materials was considered. Therefore, this was called the cradleto-gate approach. The onsite installation process, other layers and service life in conventional or alternative subbase layers were assumed to be similar, so they were not considered in the analysis. The system boundaries for both conventional and alternative layer mixes include the production of raw materials such as the extraction of natural aggregates, their processing, waste processing and transport to site as in Figure 6.

Figure 6: System Boundary Description—Cradle to Gate (own illustration)



LCA is a highly data-intensive methodology as a typical life cycle of a product or service covers thousands of human activities, which must be understood and documented in environmental reference material and energy flows (Wernet et al., 2016). The solution to close the data gaps is the use of [extensive] databases that house a great amount of data, in our case Ecolnvent. Good background data and foreground data are essential. Such information is available over a worldwide scale in the Ecoinvent database. The life cycle inventory (LCI) information involving material and energy flows considered for the processes in the study were obtained from the "Ecoinvent" database and works of literature.

The study adopted ReCiPe 2016 Midpoint method to assess the impacts. The method was introduced in 2008 (Goedkoop, Heijungs, De Schryver, Struijs and Van Zelm, 2009) and combines the strengths of other methods such as CML and Eco-Indicator 99 (Messmann, Helbig, Thorenz and Tuma, 2019). The primary objective of the ReCiPe method was to transform the long list of life cycle inventory results into a limited number of indicator scores. These indicator scores express the relative severity of an environmental impact category. This method was chosen because of its advantage with a broad set of midpoint categories and utilises an impact mechanism with global scope (Huijbregts et al., 2017). Despite the significant impact of the global warming potential proposed in the project proposal, other relevant categories were also included (Table 1).

Table 1: Different impact categories selected from ReCiPe and CED

Category Group	Impact category	Indicator	Category Indicator	
Climate Change	Global warming potential	Infra-red radiative Forcing increase	kg CO² eq	
Depletion of Abiotic	Mineral Resource Scarcity	ore grade decrease	kg Cu eq	
Resources	Fossil Resource Scarcity	upper heating value	Kg oil eq	
Acidification	Terrestrial Acidification	proton increase in natural soils	kg SO² eq	
Eutrophication	Freshwater Eutrophication	phosphorus increase in freshwater	kg P eq	
Particulate Matter	Fine Particulate Matter Formation	PM2.5 population intake increase	kg PM <sub>2.5</sub> eq	
Ozone	Stratospheric Ozone Depletion	Stratospheric ozone decrease	kg CFC11 eq	
OZUIIC	Ozone Formation Terrestrial Ecosystem	Tropospheric ozone kg NOx ed		
Cumulative energy demand	Cumulative energy consumption	Total of used primary energy	KJ	

The selected unit processes for the LCI were modified for energy and water consumption and emissions for geographic relevance to the study. In the avoided process scenario, the material aspects of avoided production of conventional materials, such as natural aggregate or sand in subbase layer and process-specific ecological backpack involved in landfill disposal were taken into account.

The following FUs are foreseen in the present project:

### Life Cycle Assessment on Road Subbase Layers Utilising Alternative and Waste Materials

The functional unit for this study was the road subbase layer of the national road class III type, where the materials were primarily produced outside the construction area. The production of the materials is undertaken within the product system. Through this methodology, emissions associated with the transport of the materials to the construction area are taken into account. The FU for the study was a one-km long class III national road with a pavement width of 6m and roadbed width of 9m that has a subbase layer of thickness 0.3m using conventional and alternative materials. Figure 8 represents the cross-section of a national road and elaborates the dimensions and the volume of the FU.

Figure 7: Vertical cross-section of a class III national road in Vietnam (own illustration)

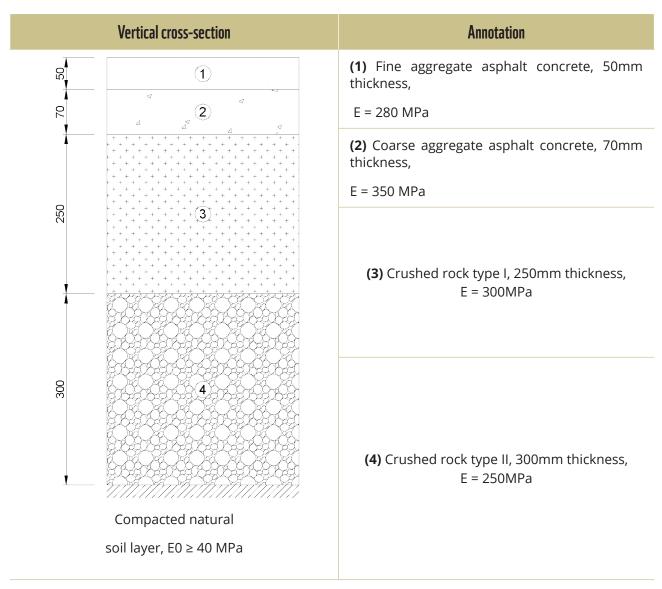


Figure 8: Functional unit for road subbase layer (own illustration)

	Functional Unit	
Road length	1 km	
Thickness of subbase layer	0.3m	Volume-based on Depth 2700 m³
Roadbed width	9 m	

#### Life Cycle Assessment on Landfill Capping Layers Utilising Alternative Waste Materials

The FU for the landfill capping construction is different for landfill layers. The materials were primarily produced outside the landfill area. The production of the materials comes within the product system. The FU for the study would be

a one-hectare area of a landfill that requires a drainage layer for several variants of a mineral sealing layer to be replaced by alternative materials mixes utilising fly ash, brick waste, rice husk ash, construction and demolition waste and brick waste. The basic FU was different landfill layers at a sample area of one hectare at their respective depth, as stated in Table 2.

Table 2: Functional unit for different landfill capping layers used in the study (own illustration)

Landfill Layers Functional Unit				
Landfill sample area	1 ha / 10000 m²	Volume-based on depth		
Depth of recultivation layer	1m	10000 m³		
Depth of mineral sealing layer	0.6m	6000 m³		
Depth of drainage layer	0.3m	3000 m³		

### Life Cycle Assessment on Non-Reinforced Concrete C25/30 Using Alternative Cement Replacement

The FU for this study was the non-reinforced concrete sample of strength C25/30, where the materials were primarily produced outside of the construction area. The production of the materials comes within the product system. The FU for the study was one cubic metre of C25-strength concrete using conventional and alternative materials replacing cement.

### Life Cycle Assessment on Non-Reinforced Concrete C25/30 Using Different Aggregates

The FU for this study was the non-reinforced concrete sample of strength C25/30, where the materials were primarily produced outside of the construction area. The production of the materials comes within the product system. The FU for the study was one cubic metre of C25-strength concrete using different aggregates.



# FINDINGS ON PRIMARY RAW MATERIALS

## 4.1 BACKGROUND AND OVERVIEW

Primary raw materials are natural resources. They are unprocessed apart from the steps needed to acquire them. The general sources of natural sand are sand pits, riverbeds and the seabed. Sand may also be obtained as manufactured sand (M-Sand or crushed sand), which is made from rocks that are crushed. Crushed sand belongs to the group of broken minerals. It does not occur naturally but is the result of rock crushing. Due to the artificial production, crushed sand has a different grain shape. This form of broken aggregate has a size of zero to about five millimetres. Up to a size of 0.25 millimetres it is referred to as fine-crushed sand. The artificial production also results in other physical and static properties for crushed sand. The typical materials that are feasible for M-Sand production are limestone, greywacke, basalt and mudstone. One must be aware that the properties of limestone, greywacke, basalt and mudstone

are different in concrete. This means that for each type of material different applications and preparation procedures for concrete production might apply. This particularly applies to the grain size and grain forms that is produced as M-Sand.

M-sand has a grain size of less than 4.75 mm and is made from crushed rock. The production line basically consists of a vibrating conveyor, jaw crusher, sand making machine, vibrating screen and belt conveyor. The properties of aggregates from natural sand deposits differ from those of broken aggregates. Natural aggregates are weathered, their surface is often smooth, and the particles are angular to rounded. In contrast, crushed sands have a rough surface structure, the particles are angular and their shape might possibly be cubic. The properties of the original rock are determined by various petrological parameters that have an important influence on the production of crushed sand, e.g., on energy consumption, on the proportion and shape of fine grain, but also on the quality of fresh and hardened concrete.



Figure 9 M-Sand samples: (from left to right): (1, left) High-quality, 0/8 mm natural glaciofluvial sand from Norway; (2, centre) Low-quality, 0/8 mm co-generated material of coarse crushed aggregate production; (3, right) High-quality, 0/8 mm crushed sand, produced using an optimised crushing circuit and shaping by Vertical Shaft Impactors. (source: https://www.metso.com/showroom/construction/new-type-of-crushed-sand-to-replace-natural-sand-in-concrete-production/)



For the production of concrete, it is important to produce rounded grains. The installation of vertical manhole machines has proven to be an effective method of producing cubic (even rounded) particles in small and medium-sized fractions (<approx. 5mm). The latest generation of dryer screening machines in combination with the latest development of air classifiers has made it possible in principle to produce crushed sand with a suitable grading curve, but this technology has not yet been used in Vietnam.

The properties of the parent rock are determined by various petrological parameters that have an important influence on the production of crushed sand, e.g., on energy consumption, on the proportion and shape of fines, but also on the quality of fresh and hardened concrete. For the production of concrete it is important to produce rounded grains. The installation of vertical shaft impactors has proven to be an effective method to produce cubic (even rounded) particles in small and medium-sized fractions (<approx. 5mm). The production of crushed sand with a suitable grain size is possible using the dry screening machines in combination with the latest development of air classifiers.

Some countries consider sea sand as a feasible primary sand resource. However, global experiences indicate substantial environmental and technical problems with offshore sand

extraction, including coastal stability problems, erosion and loss of biodiversity. . According to a feasibility study from MoNRE of Vietnam, only within Soc Trang province nearby Tran De Port, the stock of sea sand (located from 20–25 km from the shoreline) is around 1 bln m<sup>3</sup>. This is likely to be the alternative source with the largest stock in the coming years. At the moment, a standard for sea sand was developed by MoC of Vietnam. The Government of Viet Nam is planning to extract offshore sand from this province to replace river sand in four key highways in VMD. However, global experiences indicate serious problems with offshore sand extraction because of coastal stability problems, erosion and loss of biodiversity (Dybas, C.L., 2020). Several countries like Italy and Spain already forbid offshore sand mining due to threats to the coastal environment, by giving priority to nature protection (Koehnken et al. 2020). Moreover, sea sand needs a supplementary treatment (washing) as it comes from a saline environment and therefore cannot be used directly for concrete production as it causes corrosion of the concrete. This means a supplementary environmental impact. It doesn't matter what the distance is from the shoreline, sea sand extraction destroys biodiversity and leads to coastal stability problems (Dybas, C.L., 2020). From an environmental point of view, sea sand is not a viable alternative to fluvial sand and is therefore not considered in detail in the analysis.

# 4.2 POTENTIAL NATURAL SAND SOURCES

The general sources of natural sand are pit sources, river sources and sea sources connected with the challenges mentioned above. Some countries relied initially on river sand, and then later on sea sand, namely offshore sand sources. However, the global experiences indicate serious problems with offshore sand extraction because of coastal stability and erosion problems. In Vietnam, river sand sources have been exhausted.

According to the results of Kaiser (2019), there are already observed substantial coastal erosion processes in Vietnam. Coastal erosion is a problem that is increasingly affecting cities and entire provinces along Vietnam's 3,260-km coastline (Viet, 2015). This is particularly concentrated around the estuaries flowing into the South China Sea. There have always been erosive processes, not only in Vietnam, that have shaped and changed the shape of coastlines. Nevertheless, in many places in Vietnam, coastal erosion has increased significantly in recent decades due to human activities (Asplund, Malmström 2018). The erosive processes are a major problem, especially for the constantly growing sector of seaside tourism along Vietnamese beaches. The UNESCO World Heritage city, Hôi An in central Vietnam has been particularly affected by beach and coast erosion in recent decades. The coastline has receded so far that even houses have collapsed. Similar processes are taking place in the southern Vietnamese city Phan Rang-Tháp Chàm. Both cities are in proximity to estuaries. Above all, the analysis of changes in the coastline (Coastline Change Detection) plays an important role. For this purpose, remote sensing offers a suitable database to detect changes in the morphological coastal structure (Alesheikh, 2007). Through the use of geographic information software (GIS) and the statistical calculation tools integrated into it, the changes in the position of the coast lines can be determined in a spatial context with manageable effort and statistically assessed or evaluated.

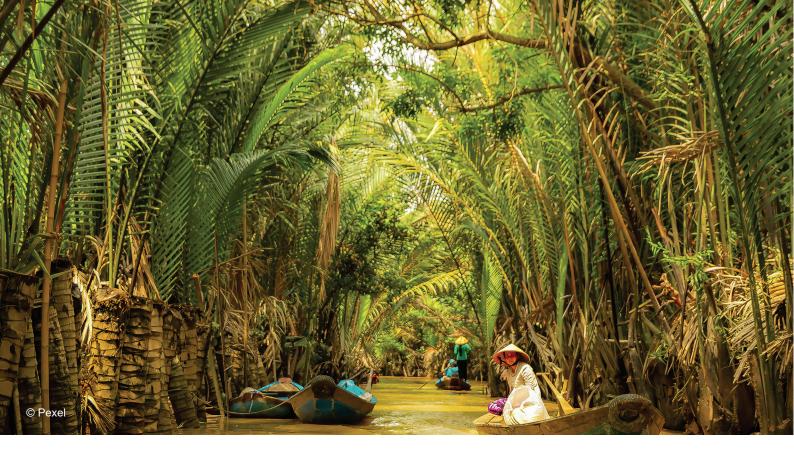
In Kaiser (2019), the coastal sections of Hội An and Phan Rang–Tháp Chàm in the immediate vicinity of the river mouths were analysed as precisely as possible for trends and erosive or statistically examined accumulative developments. In order to gain a precise and differentiated view of the

processes in two study areas, the coastal sections were divided into different sub-areas and the total study period of 31 years (1988-2019) was divided into three time intervals of 10 years each. The coastline polyline shapefiles were prepared annually from the optical Landsat satellite imagery using an unsupervised IsoClus classification and then statistically evaluated for their position change using the DSAS add-in. In the second step, an attempt was made to name reasons for the evaluated developments based on the generated data. As an example of the dimension of coastal erosion, Kaiser (2019) found that the erosion rates developed differently on the south coast of Hoi An in the period 1988–2019. In the period, 1988–1998 the erosion rates were +0.71 metres/year (no erosion but rather sedimentation), in the period 1998–2008 -4.56 metres/year (heavy erosion) and in the period 2008-2019 -0.06 metres/year (erosion greatly reduced after implementation of extensive coastal erosion control measures). The results for the dimension of coastal erosion on the north coast of Hoi An in Kaiser (2019) showed the following: In the period 1988-1998, the erosion rates were +1.47 metres/year (no erosion), in the period 1998-2008 -4 .57 metres/ year (heavy erosion) and in the period 2008-2019 -4.87 metres/year (heavy erosion). Having in view the coastal sand situation in Vietnam and Asia, an extraction of coastal sand should not be taken into consideration at all. As the river sand resources are already exhausted, only pit materials remain for M-Sand production in case natural materials are used.

# 4.3 GENERALLY FEASIBLE PIT MATERIALS FOR M-SAND PRODUCTION

In the present report, the following potential pit materials will be presented. Investigations in the SAND! Project were carried out with the following materials, e.g. rock types that are most prevalent in Southern Vietnam:

- classic sand (round)
- crushed concrete sand
- marble
- amphibolite
- granodiorite



- basalt
- broken bricks and clinker

Amphibolite, broken bricks and clinker proved to be unsuitable as sand substitutes in concrete due to a lack of stability. As a conclusion of the investigations, it can be stated that magmatic and metamorphic rocks (with the exception of amphibolite) can be used as crushed sand for the production of concrete.

With the exception of amphibolite, manufactured aggregates meet the requirements for quality concrete and achieve the required compressive strength as the formulations with natural concrete sand. The flaky grain shape of the metamorphic amphibolite leads to a significant reduction in strength. With manufactured aggregates from different types of rock (mostly magmatic or metamorphic), the same concrete quality can be achieved for all building construction purposes with good availability and short transport routes compared to river or lake dredging. For this purpose, suitability tests of the used local rock materials are to be carried out by certified concrete laboratories or material testing institutes. Therefore, the technical standardisation for the manufactured aggregates must be adapted (if they exist) so that designers and contractors have a legal basis for their work.

# 4.4 RAW OVERVIEW ON MATERIALS AVAILABILITY FOR M-SAND PRODUCTION

The analysis takes a demand-supply approach. The demand for sand was determined in HCMC through a remote sensing approach, considering the existing grey infrastructure. Moreover, data from the statistical yearbook has been considered. HCMC is the largest and most populous city in Vietnam. According to the 2019 census, HCMC has over 8.9 million residents in the city itself and over 21 million in the metropolitan area. The city is encircled by the Saigon River and includes 19 districts and 5 suburban districts with an area of approximately 2.061 km2.

The sand demand was defined in the SAND! Project in the three surrounding circles in Vietnam, namely circles of 30, 100 and 200 km with the focus at the centre of HCMC. In 2015, the total population of Vietnam was 98,869,792 (Gridded Population of the World, 2016). The number of inhabitants within each circle was given as 13,243,605, 24,652,539 and 38,505,975 which correspond to 13.39%, 24.93% and 38.95% of the total population of Vietnam (Figure 10). Although this study relates to HCMC and the surrounding area, in principle the general results can be transferred to South Vietnam.

Figure 10: Number of inhabitants within three distance variants in Vietnam (source: Gridded Population of the World, own illustration, SAND! Project).

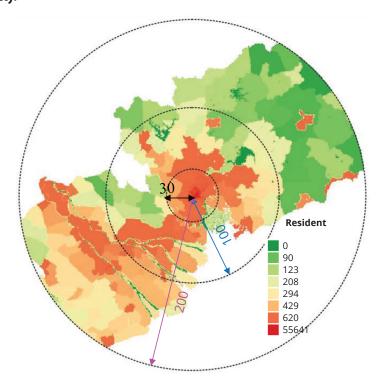
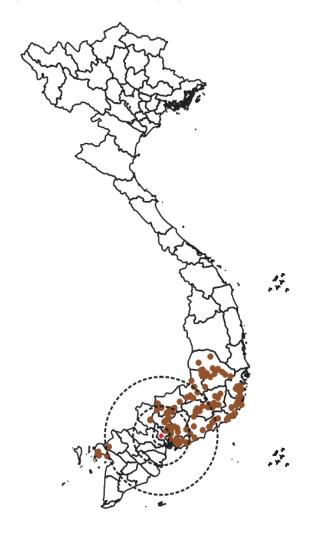


Figure 11: Location of quarry sites (own illustration, SAND! Project)



The locations of quarry sites are shown in Figure 11, but the quantity of rock was not available. In order to roughly estimate the amount of rock, the area size and the mean height of the covered area were extracted based on lithological maps and digital height maps. Three rock types were found within the 100 and 200-km circles, namely basalt (basic volcanic rocks or vb; density = 2.90 t/m3), granite (acid volcanic rocks or va; 2.65 t/m3) and mixed sedimentary rocks or smmx; 2,645 t/m3. In variant D30 (distance of 30 km to the centre of HCMC) there is only smmx with an area of 205 km2 and an average height of 13 m. The theoretical quantity could thus be calculated at 2.65E+09 m3 or 6,997 million t. All three types of rock were observed in the variants D100 and D200. The total amounts were 1,894,568 and 12,873,976 million tons for the variants D100 and D200.

Considering the aggregate mining impact on the local environment, the entire mountain is not usually mined. However, there are no set values for the percentage of quarry that can be developed to find a balance between economy and ecology. The practical amount was defined as half the natural occurrence in this study and therefore was 3,498, 947,284 and 6,436,988 million tons of rock for variants D30, D100 and D200. We estimated the theoretical annual sand requirement in the surrounding of HCMC at 6.7-8.1 million tons/ year. However, this is also only a theoretical value because it doesn't take any other land use, or the existence of remote areas or taboo zones into consideration. Such information can only be obtained from the competent authorities.

Table 3: Summaries of area size, terrain elevation, volume and weight of rock

Distance	Rock	Area [km2]	Elevation [m]	Volume [m3]	Thickness [t/m3]	Weight [mill t]
30 km	smmx	205	13	2,65E+09	2.645	6.997
100 km	smmx	2772	82	2,28E+11	2.645	602.156
	smmxvr	2329	59	1,38E+11	2.645	364.992
	va	96	92	8,82E+09	2.650	23.361
	vb	2946	106	3,12E+11	2.900	904.059
200 km	smmx	7277	294	2,14E+12	2.645	5.659.075
	smmxvr	4674	442	2,07E+12	2.645	5.466.316
	va	944	177	1,67E+11	2.650	443.496
	vb	4052	111	4,50E+11	2.900	1.305.089

Smmx = mixed sedimentary rocks\_mixed grain size; smmxvr = mixed sedimentary rocks\_mixed grain size\_subordinate volcanics; va = acid volcanic rocks; vb = basic volcanic rocks, abbreviations were taken from the digital geological map of Vietnam

Figure 12: Spatial patterns of lithology at a distance of (a) 30 km, (b) 100 km, and (c) 200 km from HCMC (source: https://aquaknow.jrc.ec.europa.eu/en/content/lithological-map-world), own illustration, SAND! Project).

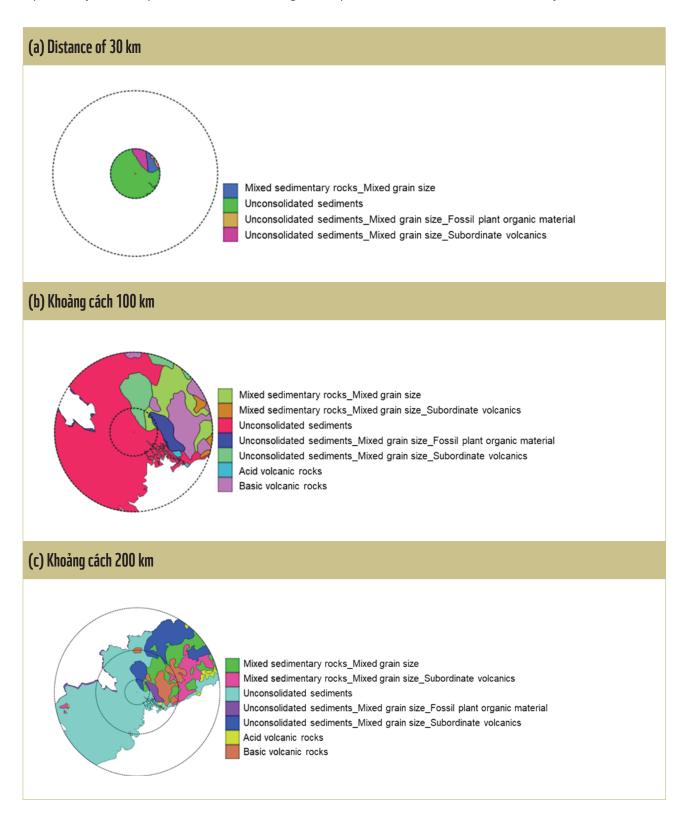


Figure 13: Spatial patterns of terrain elevation at a distance of (a) 30 km, (b) 100 km, and (c) 200 km from HCM, (own illustration, SAND! Project)

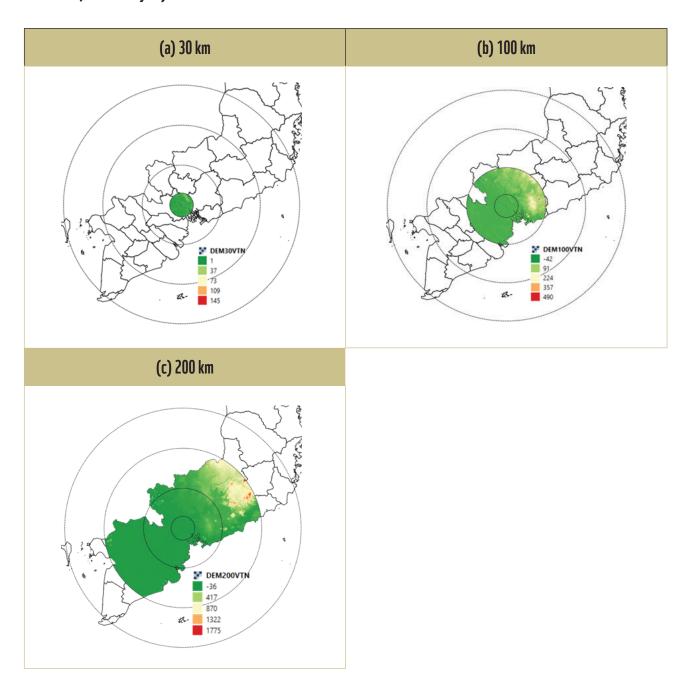


Table 4: Amount of material for three distance variants in southern Vietnam.

Distance	Reserve [mill t]	Useful [mill t]
30 km	6.997	3.498
100 km	1.894.568	947.284
200 km	12.873.976	6.436.988



It is important to be aware that these raw material estimations cannot be used as raw material reserve estimation or deposit classification for the production of crushed sand, since the rough estimate relates exclusively to the geological occurrence of the rocks. Real data for estimating a resource or reserve includes a variety of other location factors such as the potential presence of taboo zones (e.g., protected areas), other land uses (e.g., agriculture) and the land use status in general. For this reason, real resource data shall be requested from the national and local mining authorities. The recommendation for the procedure of such investigation can be found in the next section.

# 4.5 STRATEGY TO OBTAIN DETAILED DATA AND INFORMATION

The determination of potential hard rock reserves for crushed sand production must be undertaken in close cooperation with the resource and mining authorities in Vietnam. The following strategy can be followed:

 Contacting the authorities responsible for resources and mining in Vietnam

- Evaluation of geological maps with determination of the deposits of rock types suitable for the production of crushed sand
- **3.** Comparison of identified areas with official resource and reserve estimates
- Comparison of the geological information with the areal land use data and exclusion of built-up/sealed areas (GIS-based overlay of the information)
- 5. Inventory of taboo zones such as protected areas, forest, military restricted zones, infrastructure reservation areas, etc. and intersection with the geological information
- The remaining potential occurrences of suitable rocks remaining after application of all exclusion criteria are the basis for starting a technical discussion with the competent authority as to whether these areas could be available for potential sand production.

If such areas can be identified, one must be aware that it needs its investor who is interested in mining the raw materials and wants to make an investment in the exploration and permitting process.





# FINDINGS ON SECONDARY RAW MATERIALS

#### 5.1 BACKGROUND AND OVERVIEW

Secondary raw materials do not come from natural sources-at least not directly. They are obtained by recycling primary raw materials. This means that secondary raw materials are obtained through recycling. The more secondary raw materials are used, the fewer primary raw materials have to be used, thus conserving natural resources. In addition to a resource-saving, high recycling rate of the materials, long-term soil and groundwater protection has top priority. Soil and groundwater in particular are potentially at risk due to the potential harmful discharge of substances from substitute mineral building materials. It is therefore possible to differentiate between recycled building materials and mineral substitute building materials from mineral waste. Accordingly, it is not a question of recycled primary raw materials, but rather the recycling of mineral waste into building materials, hence the term "substitute building materials". The two important requirements for mineral substitute building materials are structural suitability and the exclusion of any risk to people and nature when using the mineral-substitute building materials.

Thus, substitute mineral building materials are mineral building materials that are produced as waste or by-products during construction work, are produced as waste or by-products in processing plants and are suitable for installation in technical structures immediately or after processing. Some other alternative materials which have been researched by scientists and industries across the globe to substitute fine aggregates fully or partially were glass waste, copper slag, marine dredge, fly ash, coal bottom ash, rice husk ash, quarry dust, blast furnace slag, etc. The incorporation of such alternatives in concrete, mortar, sealing layers and other applications and the end-product properties such as compressive strength, tensile strength, flexural

strength, durability, hydraulic activity etc. were studied. Substitute building materials can result from different sources. The research identified the following types of materials:

- agricultural waste,
- industrial waste,
- construction and demolition waste (CDW), including brick and concrete residues
- other sources (minor volumes)

The wastes generally have no commercial value and being locally available, transportation cost is minimal. Many waste materials are already being studied for use in concrete, bricks, mortar etc. as replacement alternatives for cement, fine aggregate, coarse aggregate and reinforcing materials. The availability of these materials in Vietnam will be investigated and assessed, as well as a characterisation of their origin, accessibility, location and expansion, including quantitative estimate per stock. Besides the material identification, localisation and parametrisation, their exploitability will be investigated given locally available technologies.

### 5.2 GENERAL OVERVIEW ON FEASIBLE SECONDARY MATERIALS IN VIETNAM

The results of the SAND! Project shows that the waste stream out of the above-mentioned material types with the highest volume is **rice husk ash** (RHA). RHA is an ideal partial replacement material for both cement and fine aggregate as it contains around 85–90% amorphous silica, providing excellent pozzolanic properties. The

use of this material type as a substitute building material creates a win-win situation. It is produced through controlled incineration between 600°C and 700°C producing and forming non-crystalline amorphous RHA. The use in construction minimises the environmental burden associated with the waste disposal problem caused by the rice milling industry. According to FAO, Vietnam generated approximately 15 million tons of rice husk in 2017 (FAO, 2018).

**Sugarcane bagasse** is the post-process fibrous residue comprising 25–30% mass composition of sugarcane. Bagasse will usually be utilised onsite in the sugar mills as a fuel source resulting in sugarcane bagasse ash. The ash contains silica (70%) or crystalline quartz based on the burning conditions. Similar to rice husk ash, sugarcane bagasse ash also depends on the temperature for increased pozzolanic reactions. The sugarcane bagasse ash has been studied widely to be used as an additive in cement, concrete and mortar mixes. The production was about 19.88 million tons of sugarcane in the year 2015/2016. One ton of bagasse is estimated to yield 24–26 kg of ash (Sales and Lima, 2010; Moretti et al., 2016).

**Coal ash,** also referred to as coal combustion residuals or CCRs, is primarily produced from the burning of coal in coal-fired power plants. Coal ash includes a number of by-products produced from burning coal, including:

- Fly ash, a very fine, powdery material composed mostly of silica made from the burning of finely ground coal in a boiler.
- Bottom ash, a coarse, angular ash particle that is too large to be carried up into the smoke stacks so it accumulates at the bottom of the coal furnace.

The forecasted power generation for Vietnam will rise from the current 47,000 megawatts (MW) to 60,000 MW by 2020 and 129,500 MW by 2030 (Vu and Gloystein, 2019). The total domestic coal consumption in 2015 was about 43.8 million tons, of which the power plants consumed 23.5 million tons and the final coal consumption was 20.3 million tons (Danish Energy Agency and MOIT, 2018).

A detailed overview on feasible materials and their availability is given below.

#### **5.3 AGRICULTURAL WASTE**

#### 5.3.1 RICE HUSK ASH (RHA)

Rice husk is the outer covering of the rice kernel, which is obtained as an agricultural waste from the rice milling process. Rice husk is abundant in rice producing countries. It has been ascertained that one ton of rice on milling yields around 200 kg of husk (i.e., 20% of paddy). This (200kg) husk on burning at controlled temperature converts to 40kg rice husk ash (Bui et al., 2011). Vietnam is one of the world's largest rice producing countries, producing 42.8 million tons in 2017. Based on the production, in 2017 Vietnam generated approximately 15 million tons of rice husk (FAO, 2018).

#### **PROPERTIES OF RHA:**

Rice husk has low nutritional value, thus making it unsuitable even for animal feed. The rice husk has half the energy value of coal and therefore it is widely used as boiler feed for rice milling purposes in developing countries (Moulick, 2015). The rice husk initially contains about 50% cellulose, 25-30% of lignin and 15-20% of silica. On incinerating the husk, it loses cellulose and lignin, with ash retaining amorphous or crystalline form of silica. RHA is whitish to greyish black in colour. The RHA obtained through open or uncontrolled burning has a high carbon content and also a highly crystalline form that is of low reactivity (Fapohunda et al., 2017). The structure of RHA depends on the incinerating conditions. Controlled incineration of rice husk between 600°C and 700°C, however, produces non-crystalline amorphous RHA (Ramezanianpour et al., 2009). Such RHA acts as a partial replacement material for both cement and fine aggregate as it contains around 85-90% amorphous silica, providing excellent pozzolanic properties (Samantaray et al., 2016). The use of RHA in concrete minimises the environmental burden associated with the waste disposal problem caused by the rice milling industry (Khan et al., 2012).

#### RELEVANCE TO REGION

To prove the amount of ash, two important databases were used in this study, namely the theoretical database and the recorded database. The theoretical data was obtained from Sciencedirect (www.sciencedirect.com/topics/engineering/rice-husk-ash). In 2017, Vietnam

was the fifth largest rice producing country in the world. Rice production has steadily increased from 27 million tons in 1997 to nearly 46 million tons in 2017. Per capita consumption of rice reached 218 kg in Vietnam in 2017. Rice husks account for about 20.25% of the weight of rice. For every 100 kg of rice husk, about 20 kg of rice husk ash is obtained. In addition, 27.9% of the husks in Vietnam is used for other purposes and 72.1% is used for rice husk burning. Rice husk ash volumes in Vietnam were obtained from the Vietnam Biomass Atlas (2018) (https://energydata.info/dataset/vietnambiomass-atlas-2018/resource/9f906779-f0df-480b-bcc3-21982eaf8774). A total of 54 rice husk incinerators in Vietnam and 46 plants within the 200-km variant around HCMC were covered.

A lot of work have been performed using RHA as a partial replacement of cement, but very little work has been undertaken for RHA as a partial replacement of fine aggregate (4.75mm or smaller).

- RHA has been used as a partial replacement for fine aggregate in the production of self-compacting concrete (SCC) and conventional concrete (CC) according to (Samantaray, Panda and Mishra, 2016). The study involves the substitution of RHA for sand in volume ratio of 0% to 50% in self-compacting and conventional concrete. A substitution of 30% RHA with sand to concrete satisfies EFNARC 2005 guidelines. The compressive, flexural and split tensile strength of SCC with RHA is more than CC with RHA.
- Kunchariyakun et al. (2015) study shows the effective replacement of readily available agricultural waste RHA for sand at a ratio of 75%–100% in the production of autoclaved aerated concrete (AAC) at a standard of ASTM C1386.
- Rumetal.(2017)investigated the substitution of RHA for sand in foamed concrete with volume ratio 0%–50%. The highest value of compressive strength was obtained at 40% RHA substitution at W/C ratios of 0.50, 0.55 and 0.60, which seemed to be higher than plain foamed concrete.
- Sathawane et al. (2013) performed a detailed experimental investigation to study the effect of partial replacement of cement by fly ash (FA) and rice husk ash (RHA) in combined proportion starting from 30% FA and 0% RHA mixed together in concrete by the replacement of cement with the gradual increase of RHA by 2.5% and simultaneously gradual decrease of FA

by 2.5%. After investigation it was reported that compressive strength increases by 30.15% compared with targeted strength, flexural strength increases by 4.57% compared with control concrete at 28 days, split tensile strength decreases by 9.58% compared with control concrete at 28 days, were obtained at a combination of 22.5% FA and 7.5% RHA. Partial replacement of FA and RHA reduces the environmental effects producing economical and eco-friendly concrete.

- Hwang and Huynh's research, (2015) shows the possibilities for utilisation of ground and ungrounded RHA from Vietnam in replacement for sand at partial ratio 30% for production of bricks under TCVN 1451:1998 Vietnam quality norms for properties such as compressive strength, flexural strength, water adsorption and bulk density.
- Suaiam and Makul's, (2014) study explored the utilisation of unprocessed lignite fly ash and rice husk ash in self-compacting concrete. Lignite fly ash was used to partially replace cement at a ratio of 0–60% and fine aggregate was replaced by rice husk ash at a level of up to 25%. The result indicated that the compressive strength of SCC containing both ≤20% fly ash and ≤25% rice husk ash exceeded 40 MPa at 180 days.
- SuaiamandMakul'sstudy(2013)reportedthe possibility of using limestone and untreated RHA as fine aggregate at various mixture ratios for self-compacting concrete. With suitable proportions of amorphous rice husk ash and limestone powder increases the compressive strength, mostly due to the micro-filling ability and pozzolanic activity of RHA according to Yu et al. (1999).
- Le et al. (2014) was able to produce highperformance fine-grained concrete with improved compressive strength, splitting tensile strength and chloride penetration resistance with the incorporation of 20% rice husk ash as add mixture.
- ThestudybyGillandSiddique(2018)utilised metakaolin at various proportions for the replacement for cement and 10% of RHA as fine aggregate substitute in self-compacting concrete. The use of both materials in SCC proved to be beneficial.
- In concrete, making, RHA needs more water than normal, because of the adsorptive character of cellular RHA particles, high porous and smaller particle size fineness

(Kunchariyakun et al., 2015) (Zareei et al., 2017). Therefore, this can be mitigated by using a Superplasticiser additive. Using less expensive and locally available RHA as a mineral add mixture in concrete brings ample benefits to the technical properties of concrete as well as to the environment. Furthermore, it is low cost. If this approach (superplasticiser additive) would be proposed to be used in Vietnam, the environmental impacts would need to be assessed separately in that context.

- Zareei et al.'s cement replacement study results (2017) indicate a positive relationship between 15% replacement of RHA with an increase in compressive strengths by about 20%. The optimum level of strength and durability properties generally gain with the addition of up to 20%, beyond that it is associated with a slight decrease in strength parameters by about 4.5%. The same results obtained for water absorption ratios are likely to be unfavourable. Chloride ion penetration increased with the increase in cement replacement by about 25% relative to the initial values (about less than one fifth). This subject is relevant in case of salty or brackish water intrusions.
- Zaid et al. (2021) reported experiments with RHA used in concrete in the presence and absence of steel fibres and concrete performance was examined. A total of nine mixes have been designed: one was a control, four were without steel fibres containing only RHA, and the last four mixed RHA with steel fibres from 0.5 to 2%. Tests with 5, 10, 15, and 20% percentages of RHA replacing the concrete have been targeted. From the results, it was noted that about 10% of cement might be replaced with rice husk ash mixed in with steel fibres with almost equal compressive strength. Replacing more than 15% of cement with RHA will produce concrete with a low performance in terms of strength and durability.
- AfurtheroptiontouseRHAintheconstruction section would be for the production of bricks. Sutas et al. (2012) performed a comparative adding between rice husk and rice husk ash which were varied by 0–10% by weight. The results showed that the addition of more rice husk resulted in less compressive strength and density of specimens. Otherwise, the porosity increases when adding rice husk. By adding 2% of rice husk ash by weight was the best of bricks properties which 6.20 MPa of compressive strength, 1.68 g/cm3 density and 15.20% water absorption.

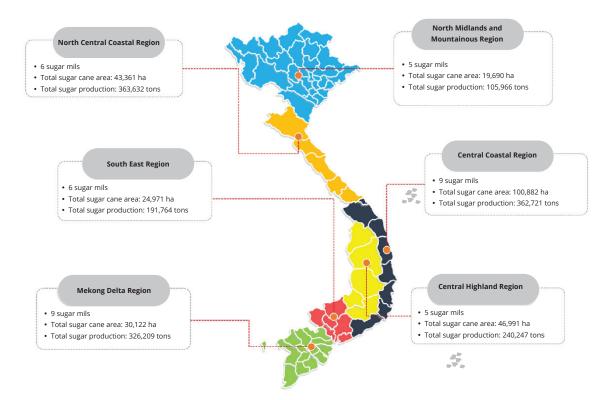
Ketov et al. (2021) stated that RHA can be reused for the manufacture of lightweight bricks. The lightweight cellular bricks demonstrate good heat insulation properties. Using rice husks ash as a raw material for foamed granulated silicates in the manufacture of lightweight ceramic bricks not only solves the problem of rice husks as a large-tonnage waste, but also provides an environmentally friendly building material with strength and heat insulation.

#### **5.3.2 SUGARCANE BAGASSE ASH**

Sugarcane is an important crop grown widely across the globe, especially with large-scale production across sub-tropical countries. The global sugarcane production was over 1700 million tons by the year 2011. With regard to the Vietnam's planned plantation area of about 305,000 ha, the production was about 19.88 million tons of sugarcane in the year 2015/2016. The current sugarcane yield for Vietnam averages about 65 ton/ha (Nguyen et al., 2022). After the implementation of a sugar program in 1995, there are currently 39 sugar mills (2016/2017) with a total capacity of 155,000 ton Cane/day (TCD). Thirty-nine sugar cane mills were located in Vietnam in 2017, (Nguyễn Anh Tú; Nguyễn Tường Khanh; GIZ, 2017). However, due to numerous recent factors such as the effectiveness of ASEAN Trade in Good Agreement (ATIGA) and the influence of the COVID-19 pandemic, the number of sugar mills dropped significantly from 39 to 29 in 2019/2020 and finally dropped to 25 in 2020/2021 (Nguyen et al., 2022), out of these, there are 5 mills in the Mekong delta (Nguyen et al., 2022).

Once the sugarcane enters the production process for sugar, it ends up as a fibrous residue comprising 25–30% mass composition of sugarcane. This residue is called sugarcane bagasse. This bagasse consists of approximately 45-50% cellulose, 20-25% hemicellulose and 25% lignin. Each ton of sugarcane is estimated to generate 26% of bagasse (Akash G. S., 2018). This bagasse will usually be utilised onsite in the sugar mills as a fuel source for steam and energy production. The resulting endproduct after the burning of bagasse is the crude residue known as sugarcane bagasse ash. One ton of bagasse is estimated to yield 140-280 kg of ash (Moretti et al., 2016; Sales and Lima, 2010, Melati et al., 2017). The bagasse ash was collected from the boilers and disposed either by landfill or used as fertilizer for the plantations, despite its low mineral nutrient value (Cordeiro et al., 2008).

Figure 14: Sugar mill distribution and sugar production capacity in Vietnam (source: MOIT and GIZ, 2017)



The bagasse ash contains silica (70%) or crystalline quartz based on the burning conditions. The ash obtained from the post burning process might have low pozzolanic activity because of uncontrolled burning (Almeida et al., 2015a). Similar to rice husk ash, sugarcane bagasse ash also depends on the temperature for increased pozzolanic reactions. The other factor affecting the pozzolanic effect was the crystallinity of the silica present in the ash and carbon/unburned impurities (Teixeira et al., 2008). Sugarcane bagasse ash has been studied widely when used as an additive in cement, concrete and mortar mixes (Cordeiro et al., 2008; Sua-iam and Makul, 2013; Almeida et al., 2015b).

#### RELEVANCE TO REGION

To detect the amount of sugarcane ash, two important databases were used in this study, namely the theoretical database and the recorded database. The theoretical data was obtained from DANVIET (2020)¹. According to the report of the Ministry of Agricultural Product Processing and Market Development, sugarcane production reaches 14,042,789 tons in the 2018–2019 harvest in Vietnam. Bagasse or dry residue is about 29.67% of the total weight (recorded value).

Each ton of sugarcane produces about 0.62% residual ash. Covered sugarcane ash incinerators in Vietnam were obtained from Vietnam–Biomass Atlas (2018)<sup>2</sup>. A total of 40 sugarcane combustion plants in Vietnam and 15 plants within the 200-km variant were considered.

- Modani and Vyawahare (2013) worked on the replacement of fine aggregate sand with sugarcane bagasse ash at range of 10–40% volume replacement to sand. The result highlights that a fraction of sand can be effectively replaced with a bagasse ash (untreated) at a ratio of 10% to 20%, without a considerable loss of workability and strength properties.
- Sua-iamandMakul(2013)workedonreplacing partial volume of sand in self-compacting concrete using bagasse ash along with limestone powder waste. The study was carried out for various proportions of bagasse ash as sand replacement and limestone powder ranging from 0–100% at individual and combined ratios. The study found advantages to using bagasse ash and limestone powder in the workability of the concrete. The SCC mix which was composed of 20% limestone powder and 20% SBA as sand alternative met the quality

 $<sup>1. \</sup>qquad \text{https://danviet.vn/san-luong-mia-che-bien-thap-chua-tung-co-trong-19-nien-vu-chi-con-29-nha-may-hoat-dong-20201016172005321.htm} \\$ 

 $<sup>2. \</sup>qquad \text{https://energydata.info/dataset/vietnam-biomass-atlas-2018/resource/9f906779-f0df-480b-bcc3-21982eaf8774)}.$ 

requirements of the European Federation of National Associations Representing Producers and Applicators of Specialist Building Products for Concrete (EFNARC) guidelines.

- In a study conducted by Moretti et al., (2016), 30% of sand was replaced by SBA and the mechanical properties of the resulting concrete was seen to be similar with a conventional reference. A combination of SBA for sand and CD waste coarse aggregate was also studied.
- A study was carried out on different compositions of concrete and mortar containing SBA as sand replacement at percentages 0-100% by Sales and Lima, (2010). The SBA samples used had a silica content of more than 75% in crystalline form and presented physical properties similar to natural sand with a fineness modulus of 0.6–1.2. Mortars produced with sand replacement at 20% and 30% of SBA exhibited higher values of compressive strength than the control sample. The concrete (slag modified Portland cement) made from 30% and 50% SBA replacement showed the best results among others. SBA can be used as a partial substitute of sand in concrete made with cement slag-modified Portland cement for design strength up to 30 MPa.
- Another study on partial sand replacement in mortar was carried out by Almeida et al. (2015b). The study involved three mortar mixes having SBA content at a ratio of 0% (Reference), 30% and 50% by mass substitute for sand at a mortar content 51.3%. It was suggested that 30% content as favourable mix because it leads the mortar to have a number of pores with larger diameters (greater than 360 nm) equivalent to the reference sample. The natural sand substitution by SBA, especially at a content of 30%, can lead to the maintenance of mechanical properties, micro pore clogging and an improvement of the durability of the mortar, in comparison with a reference mixture.

#### POTENTIAL INDUSTRY DEVELOPMENTS:

Currently, the Vietnam sugar industry is impacted largely by unstable sugar prices, high-cost cane production, low productivity of smaller mills, climate change and an increase in sugar smuggling largely from other ASEAN countries into Vietnam (Doanh, 2018). The Ministry of

Agriculture and Rural Development (MARD) is working towards restructuring the sugar industry to increase its competitiveness and sustainable development in meeting domestic demand and moving for export. Measures are being developed to increase sugarcane output to 24 million tons by 2030. More than 90% of factories are expected to process at least 4,000 tons of sugarcane each day. The industry is expected to recycle 7 million tons or 91% of bagasse annually to produce 1.5–1.6 billion kWh of electricity (Sugar Asia Magazine, 2018).

The industry is foreseeing changes and development in the coming years, indicating increased sugarcane production which also results in increased bagasse ash. On considering the future development of the industry, utilisation of the ash as a partial substitute in the construction sector can be an ideal example of sand substitute alternatives for Vietnam. Coordination between the construction industry and sugar industry and their competent authorities is required.

#### **5.4 INDUSTRIAL WASTE**

#### 5.4.1 COPPER SLAG

Copper slag, known in Vietnam as "nix grains," is a black, glassy and granulated material obtained from the smelting of copper. In South-Central Vietnam, copper slag has been used as an abrasive and blasting agent in shipyards (Tran and et al, 2013). For every ton of copper produced approximately 2.5-3 tons of slag is generated (Gorai et al., 2003). According to the Vietnam national statistics office, copper production reached 11,000 tons in 2015 (Helgi Library, 2020). Copper slag grains are angular, multifaceted, hard and dense. It is rich in iron and contains various other types of oxides, including SiO2, Al2O3, CaO and Fe3O4. The slag is generally cooled and granulated to form a sand size product with a biggest size of about 5 mm and with only a small quantity of material below 1 mm in size (Murari et al., 2015). The physical properties of copper slag are similar to those of natural sand. The incorporation of copper slag helps to reduce surface water absorption, improves the workability and leads to greatly enhanced mechanical properties for all grades of concrete (Prem et al., 2018). Copper slag is widely suitable as fine aggregate in geotechnical applications (Dhir et al., 2017). The following are some notable research works on copper slag as fine aggregate:

- Al-Jabrietal.(2011)conductedanexperimental investigation on the effects of utilising copper slag as a fine aggregate substitute on properties of mortars and concrete. The substitution was carried out at levels of 0–100% and properties such as compressive strength workability, density, compressive strength, tensile strength, flexural strength and durability were evaluated. Mortar samples containing 50% slag substitute possessed more than 70% improvement in compressive strength. The study recommends that copper slag at a ratio of 40–50% can be a potential sand replacement in concrete with good properties.
- According to Wu et al. (2010) the mechanical properties of high strength concrete using copper slag as a fine aggregate substitute up to 40% with copper slag resulted in comparable and better strength than the control sample (BS 1881 Standard). Beyond 40% replacement more voids, microcracks and capillary channels appeared in the microstructure of the concrete resulting in the premature strength damage of concrete.
- The scientific work of dos Anjos et al. (2017) focused on potential viability to substitute fine aggregate in concrete with blasted copper slag produced from abrasive blasting. Blasted copper slag was collected from construction sites, from oil storage tank outer surfaces cleaning procedure and replaced at ratios of 0-100%. An initial leaching assay test was performed to check the toxicity and it showed no toxicity. The slag residue addition improved workability and reduced the water absorption of concrete. The mechanical behaviour of concrete decreased as residue content increased, as this study also showed a decrease in compressive and tensile strength over 40% replacement of slag. Concretes with blasted copper slag do not have a tendency to prematurely age.
- MaheshBabuandRavitheja,(2019)studiedthe properties of high strength concrete utilising copper slag as a fine aggregate substitute. The replacement of slag was carried out at levels 0–100% during the first phase. The compressive, tensile and flexural strength of the concrete improved up to a replacement level of 40%. The compressive, tensile and flexural strength at 100% slag replacement were 87.18MPa, 4.69 MPa and 6.16MPa respectively, which improved further in the second phase on adding 1% nano silica to improved values 98.87MPa, 5,09MPa and 6,49MPa respectively. SEM test images show

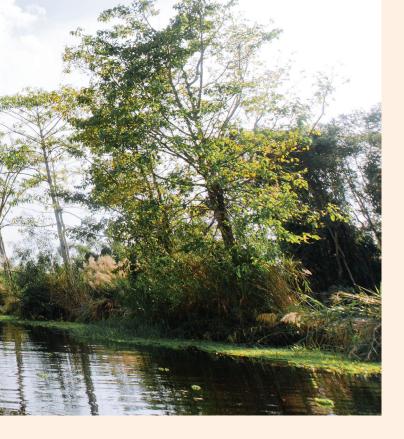
- that the addition of 1% nano silica filled all the voids, capillary channels and improved the mechanical and durable properties of concrete.
- The scientific investigation of Achudhan et al. (2018) on replacing fine aggregate with copper slag in reinforced concrete beams with 40% replacement with slag shows a compressive, split tensile and flexural strength increase of 45.8%, 19.5% and 8.2% respectively when compared to the normal concrete sample. Also, a higher level of 100% replacement showed a bleeding tendency and it was recommended that up to 80% of slag can be used as replacement of sand on a proper mix design.
- Sharma and Khan's, (2017) study evaluates the durability properties of self-compacting concrete containing fine aggregate substituted by copper slag. The copper slag was substituted at levels 0-100% at a constant w/b ratio 0.45 and tests for fresh properties, compressive strength, sulphate attack, accelerated carbonation, electrical resistivity, ultrasonic pulse velocity, initial surface absorption and sorptivity were conducted. The addition of copper slag enhanced the fresh properties of concrete. The compressive strength declined above 60% with the replacement of copper slag. During sulphate exposure the strength of samples with 20% and 40% was more than the control sample. Above the replacement of 60%, an increase in porosity of matrix and decrease in electrical resistivity was observed. This study suggests that 60% copper slag is an optimum content as partial replacement to conventional sand for either enhanced or comparable durability behaviour of SCC.
- In their research work, Gupta and Siddique (2019) designed self-compacting concrete with substituted copper slag for fine aggregate and analysed its properties and microstructure during up to 90 days of curing (EFNARC). Flowability and passing ability of SCC mixes enhanced as the content of copper slag increased, at constant water cement ratio and fixed quantity of superplasticiser. Compressive strength increased up to 30% copper slag replacement in SCC mixes at all curing ages. Beyond that, a minor decline in strength was observed, though the strength was not less than the control concrete strength. Split tensile strength augmented in SCC mixes up to 60% substitution of slag. Accumulated layers of CSH gel were observed in SCC mixes incorporating copper slag varying from 10% to 30%. The microstructure



became denser thereby increasing the strength of the concrete matrix. Ettringite crystals were observed in SCC mix with 40% copper slag under SEM analysis. In the case of SCC mixtures incorporating 50% and 60% copper slag, presence of voids, pores and micro-cracks were observed.

- A paper based on a laboratory study by Kumar (2013) investigated the feasibility of utilising copper slag as a sand replacement in mixes producing pavement quality concrete (PQC) and dry lean concrete (DLC). The replacement of slag was carried out at levels 0-100% at water/cement ratio 0.40. The slag-based PQC mixes showed an increased compressive and flexural strength when compared to the control sample. The PQC mix also showed concrete drying shrinkage and abrasion resistance decreased with an increase in slag. The compressive strength of the DLC mix decreased with the replacement of 40% slag because slag used in the study was coarser than the normally used fine aggregate and lacked the required amount of particles finer than 600µm. The study recommends a replacement of 40% slag in both PQC and DLC.
- A feasibility study for using copper slag as a replacement for quartz sand in ultra-high performance concrete (UHSC) was investigated by Rajasekar et al. (2019). The study used the copper slag in concrete mixes in a treated and untreated form. Treated copper slag involves the mechanical treatment for grinding

- copper slag to have a finer size than the standard size available, while untreated slag involves direct usage from the source. The optimum percentage replacement of unground copper slag was found to be 40%. Similarly, the incorporation of treated slag is able to produce UHSC with compressive strength of 235 MPa, flexural strength of 47 MPa and splitting tensile strength of 31 MPa with 60% ground copper slag as replacement for quartz sand. Also, chloride ion penetration is within the limits specified by ASTM C1202-12 for all treated slag sample mixes. Among the three curing regimes adopted in the study, specimens cured at elevated temperatures (steam and heat curing) have exhibited a better performance with respect to strength and durability.
- The research work (Prem et al., 2018) details the application of high-volume copper slag as a natural sand substitute in concrete production. The study used 100% sand replaced by copper slag in three different samples with water/cement ratios of 0.57, 0.47 and 0.37. Apart from the strength properties analysis, the structural performance of RC beams with copper slag are compared with companion river sand beams having shear, flexure and mixed failure modes. The compressive and flexural strength of the three mixes were higher than the control samples. The failure patterns of slag mix and control sample with river sand are however found to be similar when tested under similar loading conditions



with the same longitudinal and transverse reinforcement. The study recommends 100% replacement of sand with slag as technically viable.

- Mithun and Narasimhan's (2016) study proposes the use of copper slag as an alternative for fine aggregate natural sand in alkali activated slag concrete (AASC). The relative performance of the slag concrete is compared with conventional OPC concrete. The replacement of copper slag in the AASC shows no significant change in workability. The results show that AASC mixes with slag up to 100% show no marked loss in strength characteristics. AASC mixes with slag possess a similar modulus of elasticity, lower total porosity, lower water absorption and reduced chloride ion penetration when compared to the control opc. The deterioration rate of the control sample was higher than the AASC mix containing copper slag.
- Anexperimental study by Chavan and Kulkarni (2013) made M25 grade concrete substituting fine aggregate sand with copper slag at levels of 0–100%. The conclusion drawn is that the maximum compressive strength of concrete increased by 55% at 40% replacement of fine aggregate by copper slag, and up to 75% replacement, concrete gained more strength than the control mix concrete strength.
- According to Madheswaran et al. (2014), copper slag as a fine aggregate replacement can be up to 50% by mass for the plastering of floorings and horizontal surfaces and at

a reduced mass of up to 25% for vertical surfaces such as bricks, block walls, etc. Copper slag passing through a 2.36-mm sieve is suitable for general plastering. The slag, however is not suitable for ceiling plastering.

The feasibility study by Prasad and Ramana (2016) recommended copper slag for use in mechanically stabilised earth (MSE) walls and reinforced soil slopes (RSS) in place of conventional fill material. The evaluated gradation, physical, shear strength characteristics and electrochemical properties of copper slag met the standard specifications for a structural fill material.

#### **5.4.2 BLAST FURNACE SLAG**

Blast furnace slag (BFS) is a non-metallic by-product formed in molten conditions along with molten iron during the processing of iron ore along with coke and limestone in a blast furnace at 1,500°C. On average 300–400 kg of slag is generated per ton of molten iron. Blast furnace slag is comprised of silica, alumina and lime, combined with magnesia, sulphur, along with oxides such as iron oxide and manganese oxide (Ustabaş and Kaya, 2018; Yuksel, 2018). Based on the cooling of molten slag, there are three types of BFS: granulated, air-cooled and expanded/pelletised (National Slag Association, 2013).

**Granulated blast furnace slag**-formed by the rapid cooling of slag by water jet and ground to produce sand-like granule, widely used in cement production.

**Air-cooled blast furnace slag**-formed by cooling slowly in ambient air and processed into many sizes through a screening and crushing plant.

**Expanded blast furnace slag**-formed by the quick cooling of slag using steam or water, which results in lightweight aggregate.

Vietnam's iron and steel industry has developed rapidly in recent years. Currently, there are ten blast furnaces operated across the country. In 2017, 11.5 million tons of crude steel was produced in Vietnam (3.7 million tons more than in 2016). The finished steel production was about 24.19 million T in 2018, a 14.9% increase from 2017. Worldwide, Vietnam became the 18th largest steel-producing economy.

 Gaurav Singh et al. (2015) investigated the use of granulated blast furnace slag (GBFS) in replacing natural river sand in concrete at normal and marine conditions. The study found that the strength of concrete increases with an increase in GBFS replacement than the control concrete and decreased above 60%. The study recommended 40–50% replacement at normal conditions and 50–60% at marine conditions as an optimum ratio, when considering strength and economic factors.

- The incorporation of GBFS in concrete as a sand replacement at different levels 20%, 40%, 60% using a water/cement ratio of 0.45 and 0.5 concrete mix and various properties were studied (Patra and Mukharjee, 2017). The study pointed our that up to 40% replacement, the workability remained unchanged and at 60% replacement the workability required some addition of superplasticizer. The concrete mix at W/C ratio 0.45 with 60% GBFS replacement for sand exhibited as an ideal mix based on the different test values. The incorporation of GBS in concrete improves the quality of concrete which can be visualised from the increase in rebound number for GBSincorporated mixes.
- The possibility for using granulated blast furnace slag as sand replacement in cement mortar was studied by Nataraja et al. (2013). The researchers considered a cement mortar mix of 1:3 and GBFS replacement at levels 25–100% with a W/C ratio of 0.5. The study concluded that the compressive strength and workability of the mortar mix exhibited a marginal higher value than the control mix at GBFS levels 25–75%.
- Theresearchonusingacombinationofsilica fume (SF) and ground granulated blast-furnace slag (GBFS) available in Vietnam as a cement replacement in making ultra-high performance concrete (UPHC) by Thang et al. (2013) concluded that up to 60% of cement can be replaced by SF and GBS in variable proportions of steel fiber. The highest compressive strength of the GGBS+SF samples was attained with 20% GGBS + 10% SF under 20°C and 90°C curing, which was 158 MPa and 164 MPa, respectively.
- An experiment by Özkan et al. (2007) on the properties of concrete utilising some ratio of coal bottom ash and blast furnace slag with a slag cement and fly ash combination, the experiment showed that replacing up to 20% of sand is suitable for low strength concrete works. The experiment involved two mixes of M1 with slag cement and sand replacement with CBA and GBFS,

- while a M2 mix had slag cement with fly ash replacement at various levels. The recommended mix was M2 with 10% fly ash for cement and 10 % CBA + 10% GBFS for fine sand replacement.
- The possibility to replace iron slag for fine sand and fly ash for cement in self-compacting concrete and properties were studied (G. Singh and Siddique, 2016). Fly ash was replaced in cement at a fixed volume of 10% and sand was replaced at various levels such as 10%, 25% and 40% with iron slag. Fixed water powder ratio of 0.44 and admixture of 1.2% by weight of powder was applied in all mixes. The study results indicated that iron slag at a 40% level can be a good candidate for sand replacement for self-compacting concrete of grade M30 and M40.
- In their research, Saxena and Tembhurkar (2018) focused on replacing coarse aggregate with steel slag and using wastewater for the concrete mix. The coarse aggregate was replaced at levels of 15–100%. The results from various tests inferred that a steel slag replacement level of 50% was optimal for the concrete without any significant impact on its properties.
- The use of GGBS (ground granulated blast furnace slag) blended with bentonite and Portland cement as a liner in a landfill to prevent groundwater contamination was seen to be feasible (Devarangadi and Shankar, 2019). The results show an optimum percentage of GGBS to be used as a liner should be in the range between 15% and 20%.
- Devarangadi and M's (2020) paper reviews the use and application of two largely produced industrial by products: thermal power stations (i.e., fly ash and bottom ash) and iron-steel industries (i.e., steel slag and blast furnace slag) as a liner in a landfill in meeting their regulatory standards (i.e., 1 \* 10-7 cm/s, as per the United States Environmental Protection Agency.
- Moreover,theconstructionandthefunctional properties of a full-scale landfill top cover using steel slag was demonstrated and evaluated (Andreas et al., 2014). The tested electric arc furnace slags are suitable to be used in the foundation and equalisation layer, in the drainage layer and, mixed with cementitious slag, in the low-permeability barrier layer. The recipe for the liner

mixture should contain at least 50 wt% of cementitious slag; the particle size of the slags should not exceed about 3% of the liner thickness.

- The service quality of the blast furnace slag asphalt pavement was better than that of the conventional asphalt pavement after two years of service. Severe cracking and stripping were observed with the conventional AC pavement. These observations suggest that the service qualities of the BOF slag AC pavement were better than those of the conventional AC pavement (Lin et al., 2015).
- SoakedCaliforniaBearingRatio(CBR)values of 153% and 128% for weather slag and fresh slag respectively meet the bearing strength requirement for their use in base and subbases (Kambole et al., 2019). In addition, the low long-term expansion property of the two slag materials makes them suitable alternative materials for use in granular road base construction.
- The resistance factors were improved by adding steel slag to the crushed limestone in road pavement layers (Behiry, 2013). The use of steel slag especially at an optimal ratio, depending on the application setting, improved the subbase layer density, strength and failure resistance especially for a horizontal distance of 60 cm from load centre.
- According to Ha Thanh Le (2015), the replacement of cement by 20 wt.% FA results in higher filling ability, lower plastic viscosity and hence lower segregation self-compacting resistance of performance concrete (SCHPC) when the w/b ratio and paste volume of concrete are kept constant. The combination of 10 wt.% SF and 20 wt.% FA dramatically increases the filling ability and the passing ability, simultaneously decreasing the segregation resistance of SCHPC. The self-compacting properties of SCHPC can be controlled by the incorporation of RHA. Comparable results were already obtained by Rizwan (2006).

#### BLAST FURNACE SLAG CEMENT

According to the Slag Cement Association, slag cement can replace up to 50% of Portland cement in most common concrete mixtures, and up to

80% "in massive concrete elements and other specialised structures." Not only does it reduce CO2 emissions, but it also helps save energy. In many countries, slag is being used for cement production, such as in China, where nowadays, steel slag is a useful resource rather than a waste product since extensive applications of slag have been developed.

According to newspaper Vietnamplus (2018), "The Ministry of Construction estimated cement and clinker sales at 95–96 million tons for the full year of 2018, up by 12% over the previous year. For 2019, sales of cement and clinker are expected to post a year-on-year increase of 6–8% to reach 98–99 million tons".

On May 21, 2018, the Government issued the Document No 4721/VPCP-CN asking the ministries of construction and finance to come up with solutions to improve the efficiency of natural resources, energy and labour productivity in the cement industry as well as limiting exports (Vietnamplus, 2018).

This aims to make the cement industry focus more on the domestic market for sustainable development. Also, in May 2018, the Government asked the construction ministry to design a development strategy for the cement industry by 2030, to ensure balanced supply and demand. The construction ministry said that the top priority would be given to completing the compilation of the strategy for approval. In addition, the ministry would enhance the application of science and technology to reduce production costs, promote energy and resources savings and reduce the environmental impact of cement production."

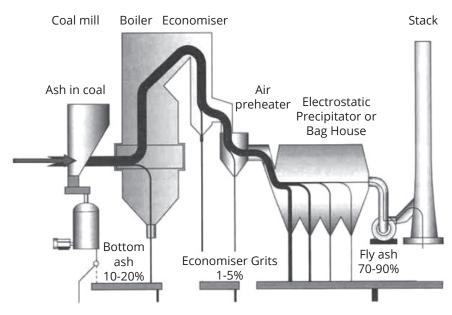
As a result of those requirements to be considered are the Government Decree 09/2021/ND-CP of February 9, 2021 on the management of building materials and the Strategy for the development of building materials in Vietnam for the period 2021–2030 with a vision to 2050, as described in section 2.

#### 5.4.3 COAL ASH WASTE

Thermal power plants form a dominating source of energy across the globe. These thermal power plants depend on pulverised coal/lignite as a fuel source to generate energy. The combustion process produces coal combustion residuals. These are by-products obtained from the combustion of coal. The coal combustion

**Figure 15: Sample of a coal fired power station scheme** (*source: bay-lynx.com, without date*)

#### **Coal Fired Power Station**



residuals are fly ash, bottom ash and flue gas desulfurisation material (figure 15). Fly ash particles are spherical and are smaller in size than cement. Fly ash can only be activated when cement is also being used. When cement reacts with water, it produces lime, which reacts with fly ash, which produces hydrated calcium silicate (CSH) (figure 15 shows a sample of one possible scheme how a coal fired power station could look like according to the producer, without date).

The quantity of coal ash generated amounts to approximately 5–45% based on the type and source of the coal. The generation of power will increase significantly in the coming years and also the ash generation remains significant. The disposal management of this waste requires large land and tedious management. The use of these waste materials has been followed in a few places at a very low level. Increased research and awareness can help to potentially explore the economic and green infrastructure values of this waste ash.

#### POTENTIAL INDUSTRY DEVELOPMENTS

With a rising population of almost 100 million and the rapidly growing economy with an annual GDP growth of around 7%, Vietnam has forecasted that power generation will rise from currently 47,000 megawatts (MW) to 60,000 MW by 2020 and 129,500 MW by 2030 (Vu and Gloystein, 2019). Currently, Vietnam has more than 20 coal-fired power plants

with a total capacity of over 13,000 megawatts (MW). The total domestic coal consumption in 2015 was about 43.8 million tons, of which the power plants consumed 23.5 million tons and the final coal consumption was 20.3 million tons (Danish Energy Agency and MOIT, 2018). Currently, 26 coal power plants exist in Vietnam (Statista, 2022). By 2030, 46 new coal-fired thermal power plants will enter operation with a total capacity of 41,500 MW. 25 plants will employ domestic coal, with a combined capacity of 18,470 MW, and 21 plants will employ imported coal, with a combined capacity of 22,780 MW (Pham et al., 2021). At present, power stations in Vietnam produce approximately 13 million tons of fly ash and plaster per year (Pham et al., 2021). Of this, only 38.9% is being used as a raw material. The amount of FA that is stored in a dump is around 25 million tons (Pham et al., 2021). The primary product utilising coal fly ash in Vietnam is gypsum boarding, used in civil construction (ASEAN Post, 2019). However, the Ministry of Industry and Trade of Vietnam has unveiled the latest draft of the National Power Development Plan for the 2021–2030 period, with a vision to 2045 (PDP VIII), outlining a roadmap to cut the share of coal-fired plants to less than 10% of the total capacity by 2045.

#### MATERIAL RELEVANCE

To prove the amount of coal and the relevant amount of ash, two important databases were

used in this study, namely the theoretical database and the recorded database. The theoretical data was obtained from KNOEMA cooperation, the enterprise datahub for IT & business leaders. The total consumption of coal in Vietnam was 74.81 million tons in 2019. Coal ash is a by-product generated when coal is burned to generate electricity. Depending on the type of coal, coal and ash demand were also estimated for the three distance options based on population share. A total of 13.2, 24.7 and 38.5 million people live within the 30-, 100-, and 200km distance ranges, respectively, representing 13.39%, 24.93% and 38.95% of the population. The recorded coal demand for power generation in Vietnam was obtained from Global Coal Plant Tracker (https://endcoal.org/tracker). A total of 175 power plants in Vietnam and 25 power plants within the 200-km variant were recorded. However, only electrical capacity was available in this database. The following method was used to convert electrical capacity to coal volume for an example of 600 MW:

Capacity: 600 MW

Working time: 8,760 h/a

 Electricity: 600 MW x 8,760 h/a = 5,256,000 MWh/a = 5,256,000 MWh/a x 3,600,000 kJ/ MWh = 1.89E+13 kJ

Energy content: 20,908,000 kJ/t coal

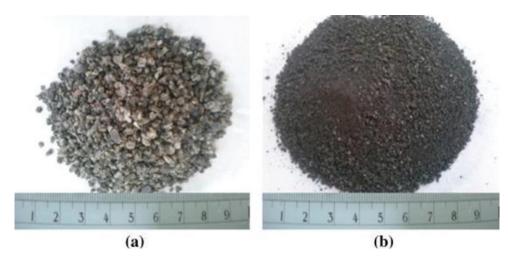
Coal demand: 1.89E+13 kJ ÷ 20,908,000 kJ/t = 904,993 t

Since not all coal was burned for energy in Vietnam, the amount of ash recorded was only between 4.1% (100-km distance) and 65% (200-km distance) of the potential values.

#### 5.4.4 COAL BOTTOM ASH

Bottom ash is a by-product obtained from the combustion of coal at thermal power plants. Coal bottom ash is granular, greyish coarse, angular, porous surface material, with a particle distribution similar to river sand. The particles have good interlocking characteristics. Bottom ash forms as a result of the melting of coal ash particles at a higher temperature than its melting point (Balasubramaniam and Thirugnanam, 2015; Abdulmatin et al., 2018). The coal bottom ash comprises nearly 20% of total ash. The chemical analysis study of coal bottom ash from an Indian plant found it to be mainly composed of silicon dioxide (56.44%), aluminium oxide (29.24%) and iron oxide (8.44%) with small amounts of calcium oxide (0.75%), magnesium oxide (0.40%), sulphate (0.24%), sodium oxide (0.09%) and potassium oxide (1.24%) etc. Some other parameters, such as specific gravity, fineness modulus and water absorption of coal bottom ash were 1.39, 1.37 and 31.58% respectively (M. Singh and Siddique, 2016).

Figure 15: Coal Bottom Ash (a) Coarse (b) Fine



- M. Singh and Siddique's (2016) study on strength and the micro structural properties of concrete containing coal bottom ash as sand replacement, highlights the increased performance of alternative concrete over conventional concrete. The study involved the utilisation of bottom ash at replacement levels 0–100% for a M20- and M30-grade concrete. The partial or full replaced concrete had higher values after 90 days curing than the control concrete and the values adhered to Indian standards.
- BasedonanotherstudybySinghandSiddique (2014) on the strength and workability of bottom ash, it was concluded that it can be partially used to replace cement in concrete. The control concrete was made in two mixtures with a compressive strength of 38MPa and 34MPa respectively at 28 days curing period. It was recommended in the study that effective bottom ash replacement at a level of up to 30% without superplasticiser and up to a level of 50% with superplasticiser based on the strength and workability is possible. It was also suggested that 100% sand replacement with bottom ash can be used when workability is not an issue such as paving blocks, pavements, hollow blocks, etc.
- The research work of Soman et al. (2014) involved the investigation of strength properties of M30 concrete made with 10–50% replacement of M-sand/crushed sand with bottom ash. The study concluded that 30% replacement of M-sand with bottom ash as optimum with marginal changes in the compressive strength, splitting tensile strength and flexural strength.
- KadamandPatil's(2015)experimentalstudy on sieved bottom ash as sand replacement in concrete also recommended that up to 30% replacement of bottom ash for sand increased the mechanical properties of concrete.
- Aninvestigationwasmade by Rafieizonooz et al. (2016) on replacing sand and cement with coal bottom ash and fly ash respectively. The study involves the replacement of 20% cement with fly ash and sand replacement with bottom ash at volumes of 25–100% in concrete. The concrete containing bottom ash at a ratio 50% and 75% exhibited better mechanical properties than control concrete at the end of 180 days of curing.

- Astudywascarriedouttoreplacethepartial level of cement in mortar with bottom ash at a rate of 20% by weight (Abdulmatin et al., 2018). The study recommends that, to use bottom ash as cement additive, it must be ground until at least 25% by weight of particles are retained on a No. 325 sieve to achieve good pozzolanic activity. Also, the chemical properties of the bottom ash should follow ASTM C618 for fly ash Class F or C.
- Wu et al (2017) investigated the feasibility of using coal gangue as landfill liner material. Their work indicates that the hydraulic conductivity of coal gangue could be smaller than the regulatory requirement 1 \* 10-7 cm/s with a void ratio of less than 0.60 (Wu et al., 2017). Concentrations of heavy metals leached from the coal gangue were all below the regulatory limits from China MEP and U.S. EPA
- The experimental results of Son (2019) show that the mixture of coal bottom ash with 11% cement, 10% fly ash with coarse aggregate and 3% cement has qualified properties of base and sub-base course layer of road pavements. This is a scientific basic for reusing coal ash from thermal power plants in Vietnam.
- Concrete experiments in the SAND! Project showed that a higher proportion of ash reduces the compressive strength (Le Hung et al. 2023). Recipes with 10% ash show higher compressive strengths than recipes with 20 or 30% ash. Compressive strength values corresponding to the basic recipe were achieved in the recipes with 10% ash 1 (bottom ash) and ash 3 (fly ash 1). The formulation with ash 2 (filter ash) has significantly lower values than other formulations and is therefore not suitable for cement reduction.

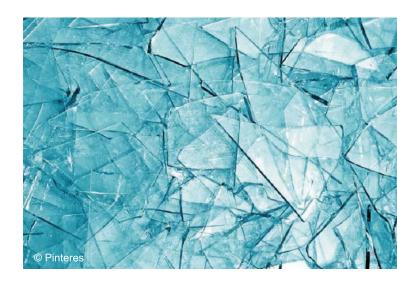
#### 5.4.5 COAL FLY ASH

Fly ash is a by-product of pulverised coal combustion in power generating plants. Fly ash is composed of fine particles residue emitted from the boiler along with flue gases in the plant, which are captured by electrostatic precipitators or particle capture units before the chimney discharge. Fly ash constitutes about 70% of total coal ash. The main components of fly ash are SiO2, Al2O3, CaO and Fe2O3, which exists in the form of amorphous and crystalline oxides. Fly ash has been classified as two types by the American Society for Testing and Materials standard based on calcium oxide content–Class C and Class F (Zhuang et al., 2016) (Bankowski et al., 2004).

**Class C fly ash.** formed on burning lignite-based source feed and has CaO more than 20 wt. %.

**Class F fly ash.** formed on burning anthracite or bituminous coal sources and has CaO of less than 10 wt. %.

- The investigation on the mechanical properties of concrete with sand replaced by class F fly ash was undertaken by Siddique (2003). The result recommends that that sand can be replaced up to 50% by weight with class F fly ash with increased compressive strength, splitting tensile strength, flexural strength and modulus of elasticity properties than conventional concrete control.
- Anassessmentonhardenedpropertiesofthe self-compacting concrete (SCC) containing a mix of raw fly ash as a partial replacement for cement (OPC) resulted in better compressive strength and other properties at 30–40% levels of replacement. The pozzolanic performance of raw fly ash was evidently observed in terms of additional strength gain at later curing stages, creating an economic concrete (Mahalingam et al., 2016).
- AnotherstudybyElmrabetetal.(2019)utilised fly ash as a partial additive to cement (OPC) development. The study recommended fly ash addition for cement production up to 35% having increased compressive strength after 90 days, with cement satisfying the quality of European norms.
- Agrawaletal.(2019)studiedanewapproachto replace sand as fine aggregate in concrete with artificial sand known as geopolymer fly ash sand (GFS) and the resulting conrete's properties. Geopolymer fly ash sand (GFS) was prepared by mixing the heated class F fly ash at 60°C in the alkaline solution containing sodium hydroxide and sodium silicate (NaOH + Na2SiO3) for 10 min at a ratio of 3:1. The molarity of NaOH was maintained at 4 M and a ratio of 2:1 Na2SiO3: NaOH was kept to make GFS cost effective (Agrawal et al., 2017). The investigation on the properties of M25 concrete made with 100% replacement of river sand with GFS resulted in the finding that the properties were marginally lower than the control concrete, but still within the limits of quality norms.
- Fly ash partially replaced sand in concrete building blocks by a study carried out



by Thomas and Nair (2015). The fly ash replacement was at levels 0–100%, with two types of concrete mix ratios 1:2:4 and 1:4:8 at varying w/c %. The results recommended blocks with 30% fly ash as being ideal for practical applications. The mix 1:2:4 satisfied the ASTM standards for load bearing masonry, while the 1:4:8 mix was recommended for non-load bearing masonry. Blocks made with 20% fly ash in 1:4:8 mix were recommended as being ideal with regard to the economical aspect for load bearing works.

- Bilir et al. (2015) studied the influence of fly ash on the mortar properties in partial replacement with fine aggregate. The mortar was prepared with sand replacement levels of 10–100% with fly ash classified as class C and F as per ASTM C 618. It was observed that fly ash at replacement levels 60–70% showed usable mechanical properties.
- Hsu et al.'s study (2018) presented an experimental investigation on the effect of replacing ground fly ash for cement in mortar. The study involved utilising fly ash ground at various fineness levels and replaced with cement at ratios of 0–20%. The mortars with fineness value of 5690 cm2/g and replacement ratio of 20% have the highest compressive strength and lowest water absorption and smallest porosity. While at fineness 4610 cm2/g and 6300 cm2/g, the replacement at 10% was recommended.
- Clay consumption across the globe is extensive and in order to mitigate the rapid consumption, an experimental study (Sutcu et al., 2019) proposed the utilisation of fly ash and bottom ash along with clay

for brick production. The study analysed various mixes of clay, fly ash and bottom ash and recommended the possibility of the development of new bricks using up to 30% by weight replacement of clay.

■ Teixeira et al. (2016) showed that the incorporation of biomass fly ashes allows for a better solution for ash disposal while contributing to the development of concretes with improved environmental performance. Despite the good results presented here, there is a need for them to be complemented by experimental studies aimed at assessing the strength and durability of pozzolanic concretes that use Portuguese biomass fly ashes as cement substitution.

#### 5.4.6 FOUNDRY WASTE

The non-ferrous and ferrous metal casting foundry industry have been utilising sand for years as a moulding material along with a binder (clay/ chemical). In general, foundry industry waste constitutes used-foundry sand, slag, ash, refractory, coagulant, baghouse dust, pattern shop waste and debris. Among them, the foundry sand waste forms a major volume, because approximately 100 million tons have been generated globally (Díaz Pace et al., 2017). The major generators of foundry sand waste are the automobile industry and its parts suppliers. The production of one ton of iron and steel metal casting required one ton of foundry sand. The waste foundry sand is subangular in shape, comprised primarily of silica with a thin film of burnt carbon, binder residuals, iron and alumina oxides (Tittarelli, 2018).

According to Vietnam Foundry and Metallurgy Science and Technology Association (VFMSTA), Vietnam produces metal castings of approximately 550,000 tons/year (www.foundry-planet.com, as of 2021). The industry uses about 70% clay-based green sand moulding (Global Casting Magazine, 2018). The green sand mould consists of high-quality silica sand (85%–95%), bentonite clay (4%–10%), carbonaceous additive (2%–10%) and water.

An experimental investigation was performed by G. Singh and R. Siddique (2012) on the effect of waste foundry sand as a natural sand replacement in strength, pulse velocity and permeability properties of concrete. The experiment involved replacing fine aggregate sand in concrete with foundry sand at 5% levels from 0–20%. The concrete mixes with foundry sand produced denser and more durable concrete with improved impermeable qualities. The study recommends a partial replacement of river sand at 15% by foundry sand in the concrete mix, which exhibited higher compressive strength, splitting tensile strength and modulus of elasticity at 28 and 91 days, thus making it suitable for structural grade concrete.

- Another study on the strength and microstructural properties of selfcompacting concrete having substituted foundry sand waste, resulted in an effective mix with substitution level of about 30% fine aggregates. The SCC mix with 30% waste foundry sand produced an economical concrete with a strength of 48 MPa (Sandhu and Siddique, 2019).
- Manoharan et al.'s research work (2018) involves the partial replacement of river sand in concrete by used foundry sand (UFS) at levels of 0–25 wt.% and analysing its engineering properties. The study concluded that the mechanical, durability and micro structural properties test results from 20 wt. % replacement of UFS were comparatively higher than the control and other mixes, thus making it as an effective replacement ratio.
- A durability study was undertaken by Gurumoorthy and Arunachalam (2019) on concrete containing treated used waste foundry sand (TUFS) as a fine sand replacement. The tests for concrete mix involved water absorption, sorptivity, strength loss and chloride permeability, with chemical and environment exposure tests. In general, foundry sand of non-ferrous foundries does not require treatment, while ferrous casting unit sand has a high iron content affecting the binding properties of concrete, which requires treatment. These sands were treated chemically and were known as treated used foundry sand (TUFS). The study established that the concrete mix containing 30% replacement with TUFS was effective under different environmental exposure from the control concrete.
- Makul and Sua-lam (2018) studied the recycling and reuse of automobile parts casting foundry sand waste in concrete production as a replacement for cement. Ordinary Portland cement was replaced at levels of 0-40% in the concrete to study their fresh concrete properties and strength

properties. Partial replacement with foundry sand increases the slump loss rate and setting time of fresh concrete, along with a decrease in unit weight. Replacing up to 30% of cement with foundry sand waste resulted in a compressive strength of 27–33 MPa at 28 days with good resistance to sulphate/sulphuric acid attack.

- Torresetal.'spaper(2017)describestheuseof processed foundry waste as fine and coarse aggregate in Portland cement concrete (PCC) for recycling of the waste and reduction of CO2. The foundry waste was processed lightly and sieved to separate the aggregates to replace at levels 10, 20 and 30% by mass, separately and combined. The properties analysis recommended that replacement as fine or coarse aggregate at 30% retained all the values as the same as the control. On a combined replacement as fine and coarse aggregate at 20% was recommended.
- Siddiqueetal.(2018)presentaenvironmental and economic benefit paper on replacing natural sand in concrete with spent foundry waste (SFW). The researchers analysed the strength and durability properties of green concrete with SFW. The replacement of natural sand with SFW was made at levels 0-20% by weight. Strength and durability properties of green concrete improved on use of up to 20% SFW as partial replacement of sand than the control. The green concrete made with fly ash-based cement and SFW reduces the negative impact on the environment by reducing CO2 emissions are more economical and consume less energy.
- An evaluation study on utilising recycled waste foundry sand as a sustainable subgrade fill and pipe bedding construction was made by analysing its geotechnical and environmental tests (Arulrajah et al., 2017). Geotechnical test results indicate that foundry sand can satisfactorily be used as fill material in embankments and in pipe-bedding applications, meeting the local road authority requirements. Environmental tests showed no environmental risks for using foundry sand in road applications, such as embankment fill and pipe bedding.
- Roads have a high potential for large volume usage of the foundry sands (Guney et al., 2006). The foundry sand along with cement and lime mixture satisfies the geomechanical as well environmental limits and can be safely used as a component in highway subbases.

#### 5.4.7 FOUNDRY SLAG

A cupola furnace is commonly used for the economical melting of metals in foundries for cast iron, Ni-resist iron, bronzes and other metals. The major by-product obtained from the process is cupola slag, which accounts for about 40–80 kg for one ton of cast iron produced. Cupola slag is a grey, crystalline and stony material. The main components of cupola slag are SiO2, CaO, Al2O3, MgO and FeO (Pribulova et al., 2019).

- Ladomerský et al.'s paper (2016) analyses the utilisation of cupola slag in granulated form as a replacement for fine aggregate in concrete products and verified its one-year mechanical properties. The study recommends a substitution of 25.5% of natural fine aggregate with ground cupola slag, which retained similar properties (workability, strength, elasticity module, pore structure, penetration of water under pressure and suction capacity) of the control sample.
- Arum and Mark's work (2014) investigated the potential partial replacement for ordinary Portland cement for low permeable concrete works. The study sample concrete mix followed a 1:2:4 ratio along with a 0.55 W/C ratio with replacement levels of 0–15%. The concrete mixes with granulated cupola slag had a higher compressive strength than the control mix (0%), with 15% cement replacement being effective with values above 25 N/mm2. The permeability of the concrete decreased with an increase in addition to granulated cupola slag for cement.
- Afolayan and Alabi's study (2013) investigated the utilisation of cupola slag as a coarse aggregate and partial cement replacement at levels of 2–10% in concrete. The slag aggregate concrete had a fixed full replacement of coarse aggregate by cupola slag and varied levels of cement replacement by grounded cupola slag at less than 75 µm diameter. The strength properties are compared with a normal control concrete and remain satisfactory.
- Cardoso et al.'s study (2018) evaluated the possibilities of the effective incorporation of ferrous metals slag (grey cast iron furnace) in construction works as a fine aggregate replacement. The slag was crushed to a fineness of about 0-2 mm and 0-4 mm. The physical properties of the slag were similar to natural sand, but with a difference in

chemical properties. The mix containing 2 mm and 4mm at 100–50% had better compressive strength making it suitable for non-concrete works.

■ The replacement of sand by grounded imperial smelting process slag (ISP) in self-compacting concrete (SCC) and its durability over chloride was studied by Szweda et al. (2017). Among the study samples, the SCC mix containing 25% granulated slag falls under the European standard requirement for minimum expected service life. A modified SCC mix should only be used for selected types of structures, where durability is not a key factor or the expected life span of a structure is shorter than the technical life span of the concrete.

#### According work (2015), cupola slags show better performance when utilised in concrete as a fine aggregate replacement than coarse aggregate. The study suggests a replacement of up to 25%.

- A comparative study looks at the possible utilisation of blast furnace and cupola slag in concrete (Baricová et al., 2010). The slags were substituted as fractions of 0–4mm; 4–8mm and 8–16mm. A combination of cupola and blast furnace slag was used, where 0–4mm grain size of blast furnace slag was replaced by cupola slag in ratios of 70:30, 80:20 and 90:10. The study recommends the use of the slag in the concrete mix as normal concrete and for less demanding applications.
- The use of cupola granulated slag as replacement of granulated blast-furnace

slag in the production of cement-free concrete has not proved to be suitable. Cupola slag may also be used as a filler material bed for water supply, sewage pipeline, gas pipeline, branch drains made of polyethylene and the reconstruction or rehabilitation works (Pribulova et al., 2019).

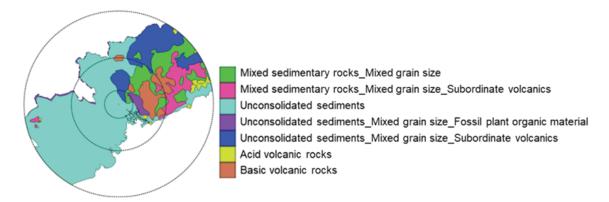
Background information on cupola or foundry slag generation and current reuse information in Vietnam could not be currently obtained. The volume output of cupola slag seems lower. A number of scientific papers on cupola slag utilisation in the construction industry suggest that this lack of information on generation and reuse is due to the comparatively low volume output of slag. .

#### 5.5 OTHER WASTE

#### 5.5.1 DUST: QUARRY, GRANITE, MARBLE

Quarry dust is the by-product of stone grinding, cutting, sieving and crushing at coarse aggregate production, available to an extent of millions of tons per year. This by-product can create many on-site and off-site environmental problems. A commonly practiced solution for quarry dust management was the incorporation in the construction industry for road construction and building materials. Although quarry dust does not possess similar granular shapes as river sand, the other physical properties and chemical composition of quarry dust seem to be comparable to river sand. Quarry dust also includes granite dust and marble dust, which are waste materials produced during the cutting and polishing process of granite and marble products.

**Figure 16: Spatial patterns of lithology at a distance of 200 km from HCMC** (own illustration, SAND! Project)



- Gupta et al.'s study (2019) focuses on the influence of quarry stone powder as a fine aggregate substitution over mechanical durability and sustainability of concrete. A substitution of higher percentages (70–100%) lowered the impact resistance and the abrasion resistance of concrete was also negatively affected. The study analyses concluded that stone processing dust (20–60%) can be used for producing structural concrete and up to 30% can be used to develop materials for the construction of pavements.
- Cheah et al.'s (2019) study aimed at the assessment of mechanical and durability properties of ternary blended cementitious composites utilising granite quarry dust (GQD) as fine aggregate. The mortarmix was comprised of ordinary Portland cement, granulated blast furnace slag and pulverised fuel ash at a ratio of 5:4:1. For the fine aggregate, river sand was replaced with granite quarry dust at levels of 10–100%. The durability performance improved up to 60% replacement and there was a marginal decrease after 80% replacement of GQD. The study concluded that GQD can be used either as a partial or complete replacement of NRS in the production of ternary blended high strength cementitious composites without significant variations in the mechanical strength, durability properties, and length change behaviour.
- A case study was presented by Kankam et al. (2017) on the stress-strain properties of concrete containing quarry dust as a sand replacement. The sand was replaced with quarry dust at levels of 0-100% for preparing C25 to C45-grade concrete. The results of the study showed that for all concrete grades, 25% level sand replacement gave higher (7.9%) modulus of elasticity (MoE) while 100% sand replacement level gave lower (8.6%) MoE relative to 0% sand replacement level. The stress strain curve of concrete with quarry dust showed 15% higher than those of conventional concrete. The study concluded that blending quarry dust and sand improved the mechanical properties.
- The influence on the flexural strength of concrete with quarry dust as sand replacement was studied by Meisuh et al. (2018). The study replaced river sand with 25% and 100% of quarry dust in concrete at a strength varying from 25 N/mm2 to 47

- N/mm2. From the results, it was observed that the flexural strength of concrete with 25% and 100% quarry dust were respectively 2% and 4.3% higher compared with control conventional concrete.
- Upadhyayaetal.'spaper(2019)describesthe analysis of physical, mechanical and bond strength of concrete containing granite quarry dust as a river sand replacement. The study involved replacing river sand with quarry dust at levels 0-40%. The results showed that a concrete mix with 20% replacement of granite quarry dust for river sand had better properties and bond strength than the reference sample.
- The feasibility of utilising quarry dust as an alternative for river sand in producing light weight concrete (LWC) was investigated by Lim et al. (2017). The quarry dust replacement was carried out at levels of 75 and 100% at different water/cement ratios 0.52–0.58. The lightweight concrete was designed at a density of 1300 ± 50 kg/m3 and a filler cement/filler ratio of 1:1 was maintained. The properties such as fluidity, compressive strength and thermal conductivity of LWC were studied. The replacement reduced fluidity and foam volume, while it increased the thermal conductivity and compressive strength.
- Venu Madhav et al. (2018) investigated the feasibility of incorporating quarry dust in geopolymer mortar as a natural sand replacement. The study used granulated blast-furnace slag and low calcium fly ash as a cement replacement and guarry waste as natural sand replacement for mortar preparation. The effect of quarry rock dust was studied as the complete replacement with the amount of GGBFS for different alkaline fluids to binder ratios of 0.55, 0.5, 0.45 and 0.4. The strength increased with an increase in age, percentage of GGBFS and also with an increase in fluid to binder ratio. It concluded that when the filler/ binder ratio was between 0.55 to 0.55. there was a consistent increase in strength.
- Abdullah et al. (2015) reported in their investigation on the impact on compressive strength and water absorption characteristics of bricks utilising quarry dust. The study used brick mix proportion of cement:sand:quarry dust at ratios 1:10:0 (B1), 1:7.5:2.5 (B2), 1:5:5 (B3), 1:2.5:7.5 (B4) and 1:0:10 (B5). The proportion mix B5 containing 100% quarry dust as a sand replacement exhibited higher compressive

- strength and low water absorption. In general, all mix proportion exhibited higher compressive strength than the reference sample according to (5 N/mm2) British Standard.
- The objective of Vijayalakshmi et al.'s (2013) study was to investigate the mechanical and durability properties of concrete utilising granite powder waste as a partial natural sand replacement. The study concluded that a partial substitution of about 15% granite powder waste can be incorporated in concrete, which does not affect the mechanical and durability properties. It was recommended to treat the granite powder by chemical bleaching to improve the sulphate resistance.
- Raman et al. (2011) presented experimental works on utilising quarry dust as a sand substitution in high-strength concrete (HSC) containing rice husk ash (RHA) as cement replacement. The study was performed for concrete mix of strengths 60 MPa and 70 MPa, according to the UK environment department. The mix had a standard 10% RHA replacement for cement and quarry dust was partially substituted at levels 0-40%. The results obtained indicated that the mixes containing 20% quarry dust were chosen as the optimum mix design for both grades of concrete, with minor negative impacts on workability. This impact can be addressed by adjusting mix design and using superplasticisers.
- Singh et al.'s research study (2016) aims for a detailed durability analysis of concrete using granite cutting waste as partial sand replacement under adverse conditions. The test was carried out for W/C ratio 0.3 and 0.4 for granite waste replacement levels at 0–70%. The performance of the concrete was tested for carbonation attack, sulphate attack, chloride ion penetration, acid attack and elevated temperature with variable W/C ratios. The results concluded that a 25% replacement of waste can be a feasible alternative for high performance under adverse conditions.
- Sharmaetal.'spaper(2017)suggeststheuseof polished granite tile waste as coarse aggregate (20mm) replacement for concrete production. The paper recommends a 20% substitution of polished granite waste for all applications and 20–40% replacement for non-structural applications such as pavements, etc.
- An experimental investigation on the physical, mechanical properties and corrosion resistance of concrete produced with granite dust as partial cement replacement was performed by Abd Elmoaty (2013). The study mixes contained cement substitution at levels of 0–15% and a W/C ratio of 0.45 was maintained as a typical concrete mix of constructions in Egypt. The use of granite dust as cement replacement at level of 5% had a positive effect on concrete along with increased corrosion cracking time.



- Vardhan et al.'s research work (2015) investigated the feasibility of incorporating marble powder waste as a cement replacement in mortar. The setting behaviour, soundness and flowability characteristics of marble powder-based mix were studied along with microstructure properties and strength development. The results of the study indicate that up to 10% of marble powder can be used as replacement of cement with no compromise on the technical characteristics and with improved workability of the mix.
- A characterisation study was undertaken by Corinaldesi et al. (2010) to use marble waste powder as mineral addition for mortars and self-compacting concrete. A sand to cement ratio of 3:1 was maintained in the study. The results in terms of mechanical properties revealed that 10% replacement of sand by marble powder in the presence of a superplasticising admixture provided maximum compressive strength at the same workability level, comparable to that of the reference mixture.
- Kabeer and Vyas's (2018) study highlights the possibility of using marble waste powder as a fine aggregate substitution in mortar mixes. Mortar mixes for masonry and rendering purposes with a 20% substitution of natural sand with marble powder was suggested. These types of mixes have a distinctively dense microstructure which is a consequence of reduced water requirement and the formation of superior quality of hydration products.
- The influence of marble waste powder used as a partial cement substitute for mechanical and durability properties of high-performance concrete was reported by Talah et al. (2015). The test results suggest a partial substitution of 15%marble waste powder for cement which positively influences the properties of the concrete with improved resistance to chloride and acid attacks.
- The main goal of André et al.'s (2014) study was to evaluate the feasibility of concrete utilising marble waste as a coarse aggregate replacement. The coarse marble waste was replaced in the study mixes at levels of 20%, 50% and 100% of primary aggregates (basalt, limestone and granite). A substitution of 20% increased the workability and a decrease was observed at 50% incorporation in mixes with limestone and basalt, whereas in granite mix it remain unchanged. The results indicate that there are no significant differences between

a concrete produced using marble waste and thus make it feasible for substitution. The study recommends, for chloride contaminated environments, additional care must be given for marble waste with low alumina.

According to Ulubeyli and Artir (2015), utilising marble waste in the conventional concrete as binder or fine/coarse aggregate has a positive effect on hardened concrete properties. But, in self-compacting or polymer concrete the properties of hardened concrete decreased.

### 5.5.2 DREDGING MATERIAL FROM WATER ENGINEERING OPERATIONS

Dredging is the process of the removal of silt, debris and other materials from the bottom of water bodies such as lakes, rivers and harbours. It is an important activity carried out regularly for safe harbour operations, off-shore activities, oil extraction etc. Dredging helps in increasing or maintaining the depth of waterways, anchorage areas ensuring safe passage of shipping, thus playing a vital role in the economy. Dredged sediment is either disposed in land or at sea causing a significant challenge on considering the volume of sediments. Dredge sediments are comprised of SiO2, CaO, Al2O3, Fe2O3, MgO, SO4 and CO2 along with heavy metal traces due to the harbour proximity (Tri et al., 2019). Sediments have a higher chloride content than seawater. A proportion of dredged sediments contains a fraction of material passing a sieve of 125µm, still, the distribution varies with regard to location and time (Limeira et al., 2011a). The dredged marine sediments can easily adsorb and accumulate hazardous materials like heavy metals. Thus, sea dumping leads to the dissemination and accumulation of pollutants in the sea and the food chain (Chen et al., 2019).

Vietnam's economic growth in the past decade has led to a significant rise in freight traffic, which highlights the importance of further development of port infrastructures to keep up the growth and reduce logistical costs for industries. The volume of cargo throughput a year at Vietnamese ports has increased by 20–30% and, as a result, government has introduced a master plan related to the development of seaport systems by 2020 and 2030 (Koushan Das, 2019). The country has 44 seaports and several minor ports, among them, the major ports include Hai Phong, Da Nang, Qui Nhon and Ho Chi Minh City.

Recent developments and studies have shown a potential reuse value for the dredged marine sediments in civil engineering applications after prior treatment. This makes a solution for the challenge of disposal and an alternative to reduce the natural resource consumption by utilising waste matter as a resource.

- Ozer-Erdoganetal.'sstudy(2016)describes the chances of beneficial usage of marine dredge (DM) in treated and untreated form as a fine aggregate replacement in ready mix concrete (RMC). The dredge sand was a composite mix obtained from different ports in Turkey, which was partially substituted with silica sand at levels 0-100%. The treatment of DM involves sieving, desalination wash, dewatering and oven drying. The dredge sand samples had low contents of heavy metals that do not cause any environmental risk. The concrete properties' analysis shows that performances of concretes containing treated DM samples were much better than concretes with untreated DM in all replacement ratios. The study concludes that 100% replacement of treated DM met the minimum requirement for C25/30 class RMC.
- Limeira et al. (2011b) worked on the analysis of mechanical and durability properties of concrete made with dredged marine sand (DMS) as a fine granular corrector in the partial substitution of raw sand at ratio of 15–50% designed for port structures such as harbour pavements. The DMS was obtained from three places in the port of Barcelona and used untreated. The DM sand had an angular shape and lower porosity than the crushed limestone sand. The results of the work concluded that the DM sand can be used as a fine aggregate replacement for the making of concrete. The fresh and mechanical properties of the concrete performed to the standards of reference 30mPa concrete and the Spanish standard for port pavement construction was achieved.
- Nguyen et al. (2018) evaluated the mechanical properties of geopolymer concrete with sea sand as fine aggregate and investigated the corrosion of steel bars embedded in the concrete. The results showed that compressive strength reached higher values at an alkaline solution (sodium silicate + sodium hydroxide) to fly ash at a ratio of 1:0.35-0.45. One of the reasons for the high compressive strength

- of sea sand geopolymer concrete was the low aggregate to fly ash ratio. At different curing conditions, the difference in strength between specimens using river sand and sea sand was not significant. The corrosion tests revealed that the potential of steel bars in sea sand geopolymer concrete was higher than in Portland cement concrete. The corrosion study requires further validation in different atmospheres required for practical application.
- An evaluation study on the durability of concrete incorporating dredged sediments 12.5% and 20% ratio suggested that marine sediments can be used in concrete (Achour et al., 2019). In a qualitative comparison, destructive and non-destructive tests showed that the quality of concrete deteriorates with the increase of the amount of fine sediments in the mix. The concrete sample with 12.5% did not show any loss in mechanical properties and had better performance for sulphate attack and freezing and thawing cycles.
- Zelleg et al. (2018) investigated the opportunities for reusing marine sediments in construction infrastructure applications. Zelleg et al. studied the utilisation in two applications such as road construction and concrete. The road construction utilisation study involved fine sediment mix with 3% lime and 3% cement. The study recommends the fine sediment mix with 3% lime as feasible reuse option in road applications. The concrete study results showed that the substitution of 20% of sand volume by fine sediments created concrete with higher compression strength than the control sample.
- A study was carried out to analyse the potential of reusing marine dredged sediment from Dunkirk as a road building material (Siham et al., 2008). The dredged sediment was treated for high water content and salinity through a dewatering process comprising treatment with 4% lime followed by thermal treatment. The experimental results showed that dredged sand and sediments can be used successfully as a road construction material for foundation and base layers of road. The mix with 6% cement was suitable for both a base and a foundation layer, while the mix with 6% blended cement (slag and limestone) can be used as a foundation layer. The mixes seem economically very competitive

with other mixtures usually used in road construction.

- An experimental study on the production of new composites using overburdened soil (40–60 wt.%) and marine dredging sludge (20–40%) with lime production waste as binder (15-30%) was carried by Mymrin et al. (2019). The study results obtained confirms that the mechanical and ecological properties of the composite made with three industrial waste products corresponded with the Brazilian quality standard. The axial resistance strength of the composite reached 5.7 MPa on the third day and 9.8 MPa on the seventh day, significantly exceeding the requirements of the Brazilian standards (4 MPa). The composite can be used for the production of construction materials such as tiles, bricks and blocks, as the base for roads and as airfield runways, dam cores, industrial and municipal waste dumps bases and building foundations.
- Alaboratorystudyonusinguncontaminated marine dredged sediments as a partial replacement for Portland cement (CEM I52.5) in concrete and mortar at three ratio 10%, 20% and 30% (Z. Zhao et al., 2018). The dredge sediment was dried at 40°C, grounded and a fraction 0/80 µm was used. The results showed that 20% sediment replacement does not require admixture and the concrete fulfilled standards on terms of total chloride content for unreinforced concrete. Nevertheless, the beneficial effect of sediment is more efficient on mortars than on concretes with respect to their mechanical properties.
- The feasibility of reusing dredged harbour sand and basic oxygen furnace slag for producing light weight aggregate (LWA) was studied by Lim et al. (2019). For the study, different preheating (400–700 °C) and sintering temperatures (1125–1200 °C) with varying dwelling time (5–15 min) were compared. The two-step production process of LWA involves preheating at 500 °C for 10 minutes followed by sintering at 1175 °C for 15 minutes. The LWA produced had very low water-soluble chloride and heavy metal leachability, thus making it non-hazardous and compliant with Taiwanese regulatory standards.
- The study of Agostini et al. (2007) proved the practical feasibility for incorporating treated marine sediments in cement-based

materials. The treatment of the sediments was undergone with a Novosol process, which was based on the stabilisation of heavy metals and the thermal elimination of organic matter. The sediment replacement of 33% and 66% were found to be feasible for cement-based and brick material applications.

There are other similar studies (Wang et al., 2017) and (Wang et al., 2012) on using dredged sediments for road works.

#### 5.5.3 GLASS WASTE

Glass is a widely used material in day-to-day life across different sectors such as packaging, construction, medical, communication, etc. Glass waste as fine aggregate replacement has been studied in several research studies. Green, amber, flint, blue, and mixed colours of glass with different particle size distribution, covering both coarse and fine aggregates in concrete mixes have been used (Dumitru and Song, 2018). Accurate data on picture screen glass in Vietnam was not available, so all types of glass were treated as a single type, namely waste glass. The direct amount of waste glass was not determined in Vietnam. However, waste glass was included in the composition of solid waste in Vietnam. Four major databases were used in this study: (Congnghiepmoitruong, 2021), (INVENT, 2009), (CENTEMA, 2009) and (Thai, 2014). The total amount of solid waste was 43,000 t/d or 15,695,000 t/a in Vietnam. By multiplying the proportion of waste glass in solid waste (1.38%), the amount of waste glass was calculated to be 215,829 t/a.

- The properties of concrete containing glass waste as a partial substitute for fine aggregate was investigated by Ismail and AL-Hashmi (2009). The fine aggregate was replaced at levels of 10–20% at a W/C ratio of 0.53 and its strength and ASR expansion properties were analysed. The concrete mix with 20% glass waste exhibited a higher compressive and flexural strength than the control mix. The glass waste reduced the ASR expansion.
- Sharifi et al. (2013) investigated the effect on properties of self-compacting concrete with partial replacement of waste glass for fine aggregate. The fine aggregate was replaced at levels 0–50% and mixes had a W/C ratio of 0.52. The fresh properties' result showed that flowability is increased



and makes the concrete suitable for the construction of normal structures, such as walls and columns. The mixes with about 5–15% glass replacement exhibited more adhesion between the glass particles and cement paste, which made a more flexural and tensile strengths.

- Bisht and Ramana's experimental investigation (2018) involves evaluating the fresh, hardened and durability properties of PPC based concrete with waste glass as a fine aggregate substitute. The substitution was carried out at levels of 18-24% with a constant W/C of 0.4. The waste glass was crushed, passed through 600 µm and retained on a 150 µm sieve. The outcome indicates that up to 21% substitution of waste glass improved the properties of the concrete mixes. FTIR analysis shows the formation of no new products. The study recommends 21% substituted mix for non-aggressive environment construction works.
- IsmailandAl-Hashmi(2009)studiedtheeffect of replacing glass waste as a fine aggregate in fresh and hardened properties of selfcompacting concrete. The waste glass was replaced with fine aggregate in proportions of 0–50% at a W/C ratio of 0.4. The study results showed that slump flow increased and that the compressive strength, splitting tensile strength, flexural strength and static modulus of elasticity of recycled glass (SCC)

- mixtures were decreased beyond a content of approx. 20% [depending on the grain size of the glass. .
- The feasibility of using ground glass in self-compacting concrete as a partial replacement for both cement and sand has been investigated in Liu's work (Liu, 2011). The research concluded that a SCC mix with satisfactory properties can be produced by replacing about 10% cement and 10% sand, without the need for a viscosity modifying agent (VMA). The strength ratio showed that glass is a promising addition in SCC.
- Boral and the Roads Transport Authority, now Roads and Maritime Services in New South Wales (Dumitru et al., 2010, 2013, 2016) investigated lab and field levels to assess the potential of fine crushed glass to be used as a partial replacement of natural sand in concrete.
- Pal and Pattnaik (2013) discussed the possibility of incorporating glass waste as a partial sand substitute in M40-grade concrete along with alcofine as an additive. The replacement was undertaken at levels 3–15%. The concrete strength increases with the addition of glass waste up to 9% due to the angular shape. The study suggests that improvements can be made by finer size of the waste glass and more alcofine addition.

- Penacho et al. (2014) characterised the physic-mechanical and performance of mortars incorporating fine glass waste as fine aggregate. The sand was replaced with glass waste at levels 0-100% at a constant aggregate size distribution in mortar. The mortars with 20% glass waste allow technically viable solutions, for which the mechanical performance and physical compatibility with the substrate are especially good. They may be used for interior applications as well as building facades.
- Eco-friendly, precast paving blocks were developed using waste glass cullet as fine aggregate at ratios 0–70% and waste glass powder as partial binder at rate 20% (Lu et al., 2019). Both the density and the water absorption were significantly reduced with the increase of glass cullet content. The paving blocks containing nearly 70% cullet as fine aggregates and 20% powder as binder satisfied Hong Kong's quality specifications.
- Ling and Poon (2011) undertook a study in which they assessed the feasibility of using CRT glass as a natural sand substitute in cement mortar. The CRT glass obtained from old TVs and monitors were acid washed for the study. The CRT glass waste replaced sand at levels 0-100% and its mechanical properties were analysed, along with the potential of the alkali-silica reaction (ASR) and leachability of lead. A cement mortar with a mix proportion of 0.75:0.25:2.5:0.45 (cement, fly ash, sand water) was prepared as the control mix and fine aggregate was replaced in other samples. The CRT glass addition increased the workability but reduced the water absorption and drying shrinkage values. The researchers concluded from the results that the properties of the CRT glass mortar mixes were similar to that of the control sample and displayed innocuous behaviour in the ASR expansion test. Also, CRT glass utilisation in cement mortar successfully prevented the leaching of lead.
- The suitability of using mortar with waste glass as fine aggregate in construction applications was also investigated by Tan and Du (2013). The fine aggregate in mortar was substituted with different glass waste samples such as brown, green, clear and mixed at levels of 0–100% at a standard proportion of ASTM C109. The mixes exhibited a reduction in flowability and density, with an increase in its air content.

There was micro-cracking and weakened bond with cement causing a compromise in mechanical properties except drying shrinkage. Durability properties were enhanced with a resistance to chloride ion penetration and sulphate attack.

#### 5.5.4 RUBBER WASTE

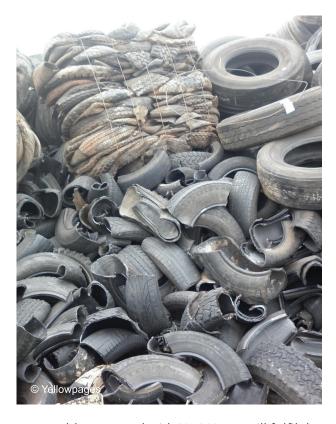
The automobile industry is growing across the world and waste tyres have been a serious waste problem across the globe. Several scientific studies have addressed the issue of waste tyre management through using a fine aggregate supplement in construction applications. The main elements present in waste tyre rubber granules are carbon, zinc, silicon, magnesium and calcium. Typical values of waste rubber particles are: specific gravity between 0.8 and 1.20 g/cm3 and water absorption of less than 3% (Topçu and Unverdi, 2018). The size of the rubber waste granules can range from a few micrometres up to centimetres, based on the grinding methods and equipment used. As per Anh's (2017) estimate, Vietnam has about 400,000 tons of tyre waste each year, of which 40% undergoes thermal treatment, 10% is reused or recycled and about 50% is disposed of in landfill and dumpsites. Also, according to the Russian trade mission (2016) in Vietnam, only 10% of the waste rubber is recycled.

- Thomas et al., (2014) investigated the possibility of waste rubber tyres as a partial sand replacement in M30-grade concrete. The concrete was designed as per IS 10262:2010 standard and rubber waste was replaced at levels of 0-20% with a W/C ratio of 0.4, 0.45 and 0.5. The tyre waste was ground into three sizes (powder form of 30 mesh, 0.8-2 mm, 2-4 mm). The three sizes of crumb rubber were mixed in definite percentages (2-4 mm size in 25%, 0.8-2 mm size in 35% and rubber powder in 40%) to bring it to zone II as per IS 383:1970. It was observed that a partial replacement for natural fine aggregates with tyre waste up to 7.5% can be used without too much reduction in its desired strength. The rubberised concrete can be recommended for the construction of pavements, structural works and nonstructural works at 7.5% replacement.
- In their study, Issa and Salem (2013) investigated the possibility of replacing fine aggregate in concrete partially by crumb rubber tyres at levels ranging from 0–100%.

The study concluded that a replacement of up to 25% was suitable and does not reduce the strength of concrete. A replacement beyond 25% resulted in a decrease of compressive strength. Up to 8% reduction in density was recorded at 25% rubber substitute. Also, enhanced ductility, insulation and damping properties were exhibited.

- An experimental study concluded that incorporated glass powder and rubber aggregates, especially with 10% and 20% increased the concrete strength (Ramdani et al., 2019). The study utilised rubber aggregate as fine aggregate replacement at levels 10-60% and glass powder was used at 15% to replace cement. The mix with 10% rubber and 15% glass powder exhibited 41.46MPa after 90 days, which was higher than the control mix. The increase in rubber waste leads to the decrease of static elasticity modulus of the concrete.
- Rashid et al.'s work (2019) focused on incorporating tyre rubber aggregates for low to medium strength concrete material. The fine and coarse aggregate was replaced at levels of 10-30%. The tyre rubber material consists of 50% car tyres and 50% truck tyres. The compressive strength was reduced more with coarse aggregate rubber substitute than with fine aggregate replacement. The result concluded the use of structural concrete with a replacement of 10% of fine aggregate with the fine rubber content. Furthermore, the replacement of 30% fine and 25% coarse aggregates by the rubber content, was the ideal solution for using concrete for medium to low strength applications.
- Abdelmonem et al. (2019) evaluated the performance of high strength concrete using waste rubber granules as a partial fine aggregate replacement. The study used four different ratios 0-30%. The compressive strength for 30% rubber replacement decreased to 35 MPa, opening a possibility of using rubberised concrete with replacement levels of up to 30% in structural elements. The rubberised concrete mixes displayed good behaviour in seawater and also showed up to 83% higher impact resistance compared to the control mix. The study suggested a mix with 30% waste rubber that can be used in structures susceptible to impact loading such as bridges and harbours.

- Waste crumb rubber was utilised in a study (Bisht and Ramana, 2017) for a pozzolana Portland cement concrete as a fine aggregate replacement at a level of 4%. The concrete had a mean target strength of 31.6 N/mm2 at w/c ratio of 0.40. The study exhibited a slight reduction in mechanical and durability properties, which was mainly due to the generation of voids due to the fineness of rubber waste. This issue can be addressed by using different gradations of crumb rubber.
- A study on static and fatigue performance of reinforced concrete slabs with crumb rubber as fine aggregate replacement resulted in 10% replacement to be ideal for the safe design of structures (Xie et al., 2019). A 10% rubber content has a relatively small impact on the fatigue life and failure mode of the slab, as well as its load-bearing capacity.
- Hesamietal.(2016) evaluated hemechanical behaviour of self-compacting paving concrete using tyre rubber as partial sand replacement and polypropylene fibre. The properties such as compressive strength, tensile strength, flexural strength, abrasive strength and modulus of elasticity decreased with the addition of rubber aggregate. But, with the addition of polypropylene fibres there was a significant increase of these properties. The result showed that a considerable rubber addition of up to 15% has no considerable negative effect on properties, which can be compensated further by the addition of fibre.
- An experimental research analysis on utilising rubber waste as fine aggregate partial substitute in high strength concrete was performed by Thomas and Chandra Gupta, (2016). The research suggests that a partial substitution of rubber aggregate up to 12.5% can result in a high strength concrete above 60MPa. The abrasion resistance and water absorption (up to 10% substitution) exhibited better results than that of the control mix concrete, making it a feasible choice for structures where there are chances of brittle failure such as pavements, floors and concrete highways, hydraulic structures such as tunnels and dam spillways, or for other surfaces upon which there are abrasive forces.
- A modified rubber concrete using waste rubber as fine aggregate replacement indicated that a 25% replacement of



rubber treated with NaOH can still fulfil the strength requirements for rigid pavements and structure construction applications (Guo et al., 2017). The study highlights that NaOH-treated methods can improve the mechanical performance of rubber concrete and enhance its long-term durability.

- Intheirstudy, Guptaetal. (2014) attempted to utilise waste rubber tyres in the form of rubber ash and rubber ash with rubber fibres as a partial replacement for fine aggregate. The study used different w/c ratios 0.35, 0.45 and 0.55. Rubber ash particles were obtained by a pyrolysis technique (incinerating waste rubber tyres at a controlled temperature of 850 °C for 72 hours) at a size ranging between 0.15 and 1.9 mm. The rubber fibres are 2-3 mm in width and are a maximum of 20 mm in length (aspect ratio 8-10) and were obtained from mechanical grinding. The study involved two mixes, where Mix 1 utilised rubber ash as a partial fine aggregate replacement at a ratio of 0-20% whereas Mix 2 had a fixed 10% rubber ash and rubber fibres varying at ratio 0-25%.
  - The workability of Mix 1 with rubber ash decreased with an increase in ash ratio, while for Mix 2 with ash and fibres did not show any effect.

- The compressive strength of Mix 1 decreased with an increase in ash for w/c ratios 0.35 and 0.45, while there was a marginal increase for w/c ratio 0.55. In Mix 2 the strength decreased with an increase in fibres for all w/c ratios.
- The flexural strength decreased for Mix 1, and for Mix 2 it increased with an increase in the fibre ratio.
- Density, water absorption and carbonation depth increase with an increase in rubber ash and fibres in both mixes.

#### 5.5.5 DESERT SAND

29% of the earth is covered by land and, of this, 33% is occupied by deserts. Despite the deserts having huge amount of sand resources, there are several reasons which have made it unsuitable as a fine aggregate sand alternative in construction industries. Desert sands are generated by aeolian processes and lack the construction grade such as small particle size, smooth rounded edge supporting less surface chemistry and not good gradation, overall making them bind less readily (Zhang et al., 2006). The technological advancements and the demand for fine aggregate have prompted the need to look for possibilities to use desert sand as fine aggregate alternative. There are few prominent researchers who focus on this aspect.

- Neumann and Curbach, (2018) from the Technical University of Dresden have been patented a method to process desert sand in order to utilise it as fine aggregate in construction. The method is based on a sintering process, which allows the reshaping of solids by combining single particles. The process occurs under the melting point to keep the crystalline structure of grains avoiding amorphous states. Researchers at the Technical University of Dresden have successfully tested the method with different types of desert sand, which were sintered to produce aggregates. The production of aggregates with varying but distinct grain sizes allows the entire substitution of conventional aggregates with those made from desert sand.
- Zhang et al. (2006) studied the feasibility of utilising superfine desert sand from



China as a fine aggregate by analysing the performance of mortar. The mix used Tenggeli desert sand and Maowusu sand along with admixture CBC and CMS consisting of a surface activator, plasticiser and coagulant. The researchers concluded from the study that the application of desert sand in civil works is feasible. The workability of mortar was extremely poor when the cement/sand ratio is lower than 1:2. Therefore, it was recommended to use desert sand as coated mortar at a higher ratio than 1:2. The admixture addition improved the workability and increased the compressive strength properties.

An investigation on concrete incorporating dune sand was carried out in Oman (Al-Harthy et al., 2007) and its effect on workability, compressive strength, tensile strength, modulus of elasticity and initial surface absorption test (ISAT) was studied. Concrete using OPC cement designed at a compressive strength of 40 N/mm2 with dune sand at partial replacement levels with crushed sand 10–100% was analysed. The study highlighted that despite the poor gradation of dune sand, it can be used in concrete on adopting a mix without negative effects. The compressive strength reduced with an increase in dune sand content. However, this decrease was small, with the maximum reduction in strength being less than 25%. The

surface absorption increased with an increase in dune sand, but did not have any effect on the elasticity modulus. The study recommends dune sand up of up to 60% and the adoption of a lower water to cement ratio. The use of slag cement can reduce surface absorption.

- A replacement of fine aggregate with dune sand up to 50% in self-compacting mortar resulted in improved flowability without any negative effects. Furthermore, the compressive and flexural strength remained constant after 28 days at a nominal increase in dune sand. Minimum compressive strength and flexural strength occur with higher replacement content of dune sand according to Benabed et al. (2014).
- Desert sand was partially used in making low volume asphalt road pavements comprising 63% M-Sand and 33% desert sand along with high performance bitumen PG70-10. The chosen binder allows the higher addition of desert sand and overall improved durability. The mix used in the study (Almadwi and Assaf, 2019) shows economic advantages for low volume roads in remote regions and in hot and dry regions.
- Amixofceramicwasteanddunesandmortar showed the best mechanical performance



under different curing environments (Abadou et al., 2016). Furthermore, the modified mortar mixes exhibited more resistant to the sulphuric and hydrochloric acid solution attack. The compressive strength of dune sand ceramic mortar reaches good strength at a 40% and 50% mix ratio of ceramic at different curing conditions.

■ Lee et al. (2016) reported that a concrete mix with crushed sand and 20% dune sand exhibited higher compressive and tensile strength in their study. The strength decreased with an increase in dune sand above 20%. In the study, lower water content of mix led to higher net time-to-cracking.

## 5.6 CONSTRUCTION AND DEMOLITION WASTE (CDW)

### 5.6.1 CRUSHED CONCRETE FOR THE PRODUCTION OF RECYCLED CONCRETE

The production of recycled concrete from concrete demolition materials is a common worldwide practice (Marinkovic et al, 2010; Perkins et al. 2021). With regard to the technical properties, it will not be examined further here, but will be

assumed as given. The production of concrete, the design and construction of concrete parts, the determination of properties and application rules in construction are regulated in the standard TCVN 7570:2006 "Aggregates for concrete and mortar—Specifications". The main requirements for alternative primary sand sources are laid down in the norm TCVN 9205:2012 "Crushed Sand for Concrete and Mortar".

However, according to information of the Asian Development Bank (2014), the CDW stream is not yet large in Vietnam, and supposed to increase starting from 2040, when parts of the existing infrastructure will need to be replaced or upgraded. This will result in CDW as another key feed-stock for road construction as backfilling or building material instead to be dumped into landfills or the natural environment (Mihai, 2019). Lockrey et al. (2016) estimated the total amount of CDW in Vietnam in 2020 amounted only to 6.3 million tons and will reach 11 million tons in 2025. Moreover, only 1-2% of CDW was estimated to be recycled yet in Vietnam (Thai et al, 2022). In the last two decades, the direct material input (DMI) of the HCMC metropolitan area was mainly composed of biomass, totalling 22.6 million tons (43% of the DMI); non-metallic minerals, totalling 22.1 million tons (42%); and fossil fuels, totalling 5.2 million tons (10%). The main subcategories of biomass entering HCMC were agricultural biomass (55%), wood (23%) and

unspecified biomass (18%). The most significant non-metallic minerals were stones, representing 77% of the total non-metallic minerals; and sand, representing 22%. Fossil fuels were mainly of the low-ash type, accounting for 55% of all fossil fuels. Together, these six subcategories of materials accounted for 89% of the DMI of HCMC.

#### **5.6.2 BRICK WASTE**

Since there is no recorded data for brick quarries in Vietnam, a theoretical total was used in this study. Lockrey et al. (2016) estimated the total amount of construction waste generated in Vietnam in 2020 to be 6.3 million tons. The number of broken bricks was difficult to determine, so this amount was converted based on share (17%), therefore the amount of brick was estimated to be 1.07 million tons.

- Dang and Zhao's (2019) work describes the utilisation of waste fired-clay bricks as fine aggregate at variable replacement rates 0–100% with different volumes of water addition in concrete. The study focused on the mechanical and microstructural properties of the concrete. The compressive strength of the waste clay brick concrete at 50% replacement was comparable to normal concrete.
- ThestudybyDebiebandKenai(2008)suggests the possibility of using brick waste as a replacement at 25% for coarse aggregate and 50% for fine aggregate. Recycled brick aggregates present relatively lower bulk density and higher water absorption compared to natural aggregates.
- Lietal.(2020) adopts substituting a portion of the paste by an equal volume of clay brick dust (CBD) without changing the paste composition and water/cementitious materials ratio to produce mortar. It was shown that up to 20% CBD by volume of the mortar may be added to reduce the cement content by 33% without causing adverse effects.
- The compressive strength of foam concrete with clay brick powder up to 15% had a similar or even higher strength than that of the normal foam concrete. Incorporating brick powder reduces the

- drying shrinkage of foam concrete and the maximum shrinkage ratio (Yang et al., 2020).
- Brick waste was used at a ratio of 35–45% replacement for fine aggregate at different water binder ratios (0.2, 0.3, 0.4) in lightweight concrete. The concrete reached a strength up to 40MPa, thereby meeting Chinese requirements. The lower W/B could result in higher compressive strength, but the differences of compressive strength among mixtures with various W/B are gradually decreased with time (Y. Zhao et al., 2018).
- The study (Dang et al., 2020) using brick waste as sand replacement at 50% and, 100% replacement resulted in the reduction of chloride migration, but increased the water absorption, water sorptivity, drying shrinkage and carbonation. The water absorption, water sorptivity and carbonation can be minimised by reducing the additional water content. The microscopy results show that the pore structure of concrete deteriorates with the increase in the replacement because of the porous structure of brick waste.
- The compressive stress-strain behaviour and mechanical properties of clay brick masonry and its constituents clay bricks and mortar showed that cement mortars with 20% replacement of fine aggregate with clay brick waste exhibited a higher compressive strength than control. The compressive strength is more than controlled mortar for replacement ratio of sand with clay brick waste up to around 35% for a curing period of 3 and 28 days and 25% for a curing period of 7 days (Kumavat, 2016).
- The CBR values decreased as the replacement level of recycled concrete aggregates by crushed clay brick increased in the study (Poon and Chan, 2006). Nevertheless, the soaked CBR values for all recycled subbases were greater than 30%, which is a minimum strength requirement in Hong Kong. Furthermore, the recorded percentage swells for all subbases and were less than 0.13% which can be considered as being negligible.



## SUSTAINABILITY ASSESSMENT: LCA FINDINGS

#### 6.1 OVERVIEW

The LCA has been carried out on different selections of the materials presented above. In the following sections, the results of the sustainability assessment for the following applications of four to seven selected substitutive building materials are summarised:

- LCA on Road Subbase Layers Utilising Alternative and Waste Materials
- LCA on Landfill Capping Layers Utilising Alternative and Waste Materials
- LCA on Non-Reinforced Concrete C25/30
   Using Alternative Cement Replacement
- LCA on Non-Reinforced Concrete C25/30
   Using Different Aggregates

The selection is based on the present or future availability of the materials in Vietnam, and their feasibility.



# 6.2 LCA ON ROAD SUBBASE LAYERS UTILISING ALTERNATIVE AND WASTE MATERIALS

#### 6.2.1 GENERAL BACKGROUND

Road transport plays an important role in transport infrastructure in Vietnam because of its high mobility, excellent distribution and doorto-door features. In Vietnam, road transport accounts for more than 77.4% of the volume of transported goods and 94% of passengers (gso. vn, 2018). According to Huu and Ngoc (2021) in the past five years (2015–2020) in Hanoi, the ratio of transportation land area to urban construction area has increased by only 0.3% each year. Vietnam has six classes of roads which include national motorways, provincial roads, district roads, rural roads, urban streets and special roads for government officials. In Vietnam, common pavement types are asphalt concrete, cement concrete, bitumen treated crushed stones, crushed stones and soil.

In contrast, each type consists of a specific number and a combination of layers (Schiller, Bimesmeier and Pham, 2020). The road embankment, serving as the foundation or sub-base, consists of soil mobilised from cutting slopes/sections along the road or natural sand. Table 5 below shows the different classes of roads in Vietnam and their average width (Schiller et al., 2020).

Table 5: Different types of roads in Vietnam

Road Type	Class/Type	Average Width (m)		References		
	ciassy type	Design Speed	Average Width (m)	Neterelices		
Expressways	Cấp I (60 km/h)	14	22			
	Cấp II (80 km/h)	14	22			
	Cấp III (100 km/h)	15	24.75			
	Cấp IV (120 km/h)	15	24.75			
Highways	Cấp I (120 km/h)	22.5	32.5			
	Cấp II (100 km/h)	15	22.5	(Schiller et al.,		
	Cấp III (80 km/h)	7	12	2020)		
	Cấp IV (60 km/h)	7	9	TCVN 5729:2012		
	Cấp V (40 km/h)	5.5	7.5	TVCN 4045:2005		
	Cấp VI (20 km/h)	3.5	6.5			
National roads	Cấp III (60 km/h)	6	9			
	Cấp IV (40 km/h)	5.5	7.5			
	Cấp V (30 km/h)	3.5	6.5			
	Cấp VI (20 km/h)	3.5	6			

There is a huge potential for road project developments across the Vietnamese region because of its rapid urbanisation. According to Anh Duy (2019), the ministry has plans to extend the road network plan for 2020 with a vision to 2030 across the country involving building new routes to major seaports, linking cities and business centres. National roads often provide local access, catering primarily to interprovincial traffic. The report (JICA and MOT, 2010) highlights the need in Vietnam for national roads network expansion by at least 10,000 km by 2030 for the network coverage to be considered well-developed. Future network development needs vast quantities of aggregates, which might

put pressure on the existing resource budget. Therefore, it would be a strategic and sustainable advantage to adopt secondary waste materials as a resource in future developmental projects. Among the alternatives, it would be essential to identify sustainable, low global warming potential and environmental materials with low carbon footprints when considering the climate change situation. The table below elaborates different mixes of road subbase considered in this study, such as manufactured sand (M-Sand), granulated blast furnace slag (GBF), electric arc furnace slag (EAF), construction demolition waste (CDW) and fly ash (FA).

Table 6: Mix ratio of different materials for subbase layer used in the comparative study

Subbase Layer						
Conventional Subbase	Sand					
	100%					
Alternative		M-sand	CDW	GBF slag	EAF slag	Fly ash
Subbase		100%	100%	100%	100%	100%

#### **6.2.2 LIFE CYCLE ASSESSMENT**

Roads are critical infrastructure for passengers and freight transportation, one of the predominant drivers for socio-economic development. Roads play the role of providing a stable structural and durable surface for vehicles. Road construction relies on the utilisation of virgin natural aggregates as building materials. However, growing pressures for sustainable roads highlight the importance of replacing virgin materials with industrial byproducts. Aggregates with good geotechnical characteristics are becoming increasingly scarce. The authorisation processes for the extraction of natural deposits are getting progressively rigorous. Therefore, it would be a strategic and sustainable advantage to adopt secondary waste materials as a resource in future developmental projects. Table 6 elaborates on different mixes of road subbase considered in this study, such as manufactured sand (m-sand), granulated blast furnace slag (GBF), electric arc furnace slag (EAF), construction demolition waste (CDW) and fly ash (FA).

### 6.2.2.1.1 FUNCTIONAL UNIT AND SYSTEM DESCRIPTION

The functional unit for this study was the road subbase layer of a class III-type national road, where the materials were primarily produced beyond the construction area. The production of the materials is incorporated within the product system. The functional unit for the study will be a one-km long class III national road with a pavement width of 6 m and roadbed width of 9 m that has a subbase layer of thickness 0.3 m using conventional and alternative materials. Table 7 elaborates on the dimensions and the volume of the functional unit. In this LCA analysis, only the production stage involved in the supply of raw materials and alternative materials was considered. Therefore, this was called the cradleto-gate approach. The onsite installation process, other layers and service life in conventional or alternative subbase layers were assumed to be similar, so they were not considered in the analysis.

Table 7. Functional Unit for road subbase layer used in the study

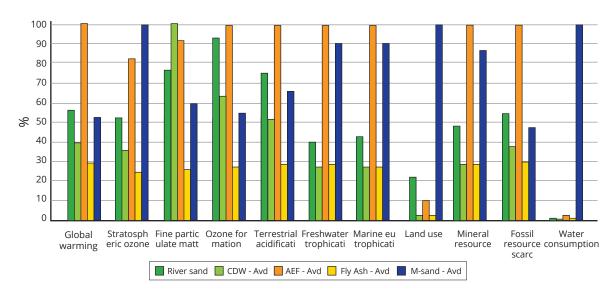
Functional Unit				
Road length	1 km			
Thickness of subbase layer	0.3 m	Volume-based on depth 2700 m³		
Roadbed wide	9 m			

#### LCA comparison of road subbase layernormal scenario

The normal scenario involves comparing conventional river sand-based subbase layers and alternative material-based subbase without considering the avoidance of using alternative materials. In this comparison, EAF slag has a higher GWP impact than the other materials (Figure 17). All other alternative materials, in general, have a lower GWP contribution than the river sand layer. Overall, GBF slag has approximately 7 times higher impact than all other materials. Therefore, the comparison of GBF slag and conventional river sand was kept separate to better understand other alternatives. The GWP contribution analysis of the different material-based layers in a normal scenario indicates that more than 52% of the CO2 footprint was associated with the transportation process than the material processing stage for all materials except GBF slag, which has about 91.5% from material processing. The entire GWP impact arises from the transportation process for fly ash as the material production carries a zero allocation. The contribution of GWP from transportation remains very low when compared to material processing in GBF slag use.

Compared with EAF slag, the CDW layer has 61% and fly ash has 70.7% lower GWP impact contribution among the alternative materials. In the mineral scarcity impact category, the CDW and fly ash layers exhibited 71% lower impact than EAF slag and 19% lower than river sand. In general, among the alternatives except for GBF slag and M-Sand, other alternative materials possessed a very low level of land use and water consumption impacts. The impacts generated from the GBF slag were seen as higher than all other materials (Figure 18).

Figure 17: Life cycle impact analysis for different subbase layer mix (not icluding GBF)—Normal Scenario (own illustration, SAND! Project)



Overall, GBF slag has approximately 7 times higher impact than all other materials. The higher ratio would arise because steel processing was a very energy-intensive process made from abiotic materials and blast furnace slag was a residue of those processes. Large energy consumption has impacts on GHG generation, ozone formation, and furthermore, it might produce fine particulate matter. In parallel, steel manufacturing uses

abiotic or materials that lead to resource scarcity and higher water consumption, land consumption and eutrophication. Therefore, the comparison of GBF slag and conventional river sand was kept separate in order to have a better understanding among other alternatives (Figure 18).

Figure 18. Life cycle impact analysis for different subbase layer mix-Normal Scenario (own illustration, SAND! Project)

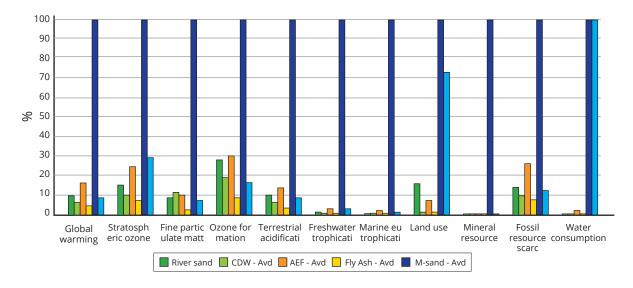
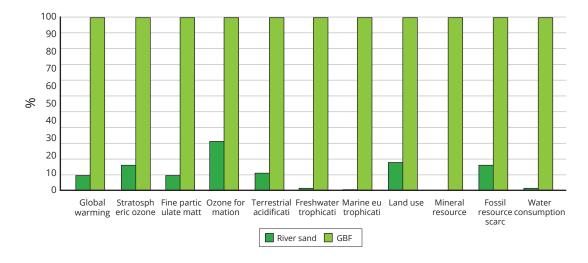


Figure 19. Life cycle impact analysis for different subbase layer mix—Normal Scenario (own illustration, SAND! Project)



#### **Energy demand analysis-normal scenario**

In a normal scenario without GBF slag, the EAF slag subbase layer has the highest energy demand across most categories (Figure 20). All other alternative mix layers possess a lower energy demand in the fossil-based category than the conventional river sand layer. Overall, across

all energy source categories, the energy demand remained low for the fly ash mix layer. The water-based renewable energy share was highest for the M-Sand layer. Figure 21 shows that GBF slag has a high energy demand of about nine times higher than the conventional sand layer. This indicates that steel processing is extremely energy-intensive.

100 90 80 70 60 850 40

Non-renewable

River sand CDW - Avd AEF - Avd Fly Ash - Avd M-sand - Avd

Renewable

Renewables - wind,

solar, geothermal

Regeneration

Figure 20. Energy Demand Analysis for different subbase layers—Normal Scenario (own illustration, SAND! Project)

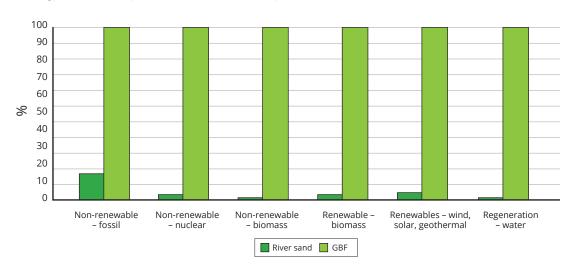


Non-renewable

- nucleai

Non-renewable

- fossil



#### LCA comparison of road subbase layeravoidance scenario

The avoidance scenario involves comparing the conventional subbase layer and alternative material subbase layers with the avoided process to technosphere factors. In this comparison (Figure 22) a conventional river sand layer has a higher GWP impact than the other materials. All other alternative materials, in general, have a lower GWP contribution than the river sand layer. Like the normal scenario, an overall GBF slag has approximately 7 to 8 times higher impact than all other materials. The comparison of GBF slag and conventional river sand, therefore, kept separate from having a better understanding among other alternatives. Among the alternative materials, CDW has the least impact.

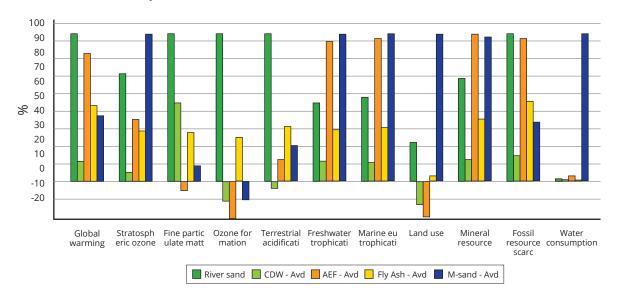
The contribution analysis in avoidance scenario shows that among the alternative layers except for GBF slag, all the alternative layers only had a carbon contribution from the transportation process. Their material processing carbon contribution was negative or zero. The construction waste layer had a GWP reduction of about -66%, EAF slag about -37.6% and m-sand about -16.8% in the material processing area compared with the conventional river sand layer. The alternative materials usage shows a negative GWP impact in material processing stages.

Over the other impact categories, the GBF slag layer had the highest impact across all the alternative layers (Figure 23). The M-Sand layer exhibited a higher water consumption impact than the GBF slag layer, which was almost 62% higher. In general, CDW, EAF and fly ash showed a minimal environmental footprint in the avoidance

scenario. In the ozone formation impact category, the CDW layer, EAF layer and m-sand layer showed some negative reduction. Notably, the CDW and EAF slag layer showed a negative reduction benefit in land use impact categories, which were -16.8%

and -25.8% respectively. Water consumption remains highest for the M-Sand layer and least for CDW layer within the alternatives. Among the alternative layers CDW, EAF and fly ash exhibits lower or negative land use impact.

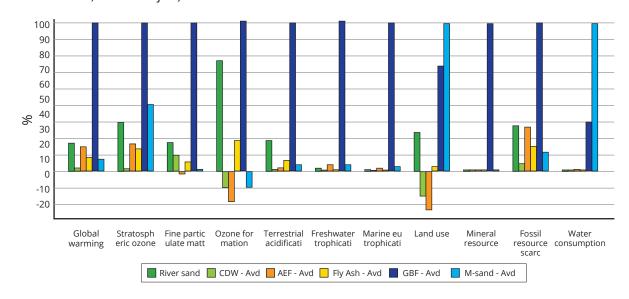
Figure 22. Life cycle impact analysis for different subbase layer mix (not including GBF)-Avoidance Scenario (own illustration, SAND! Project)



The blast furnace slag layer exhibits the highest impacts similar to the normal scenario despite avoidance allocations in this scenario. The comparison of GBF slag

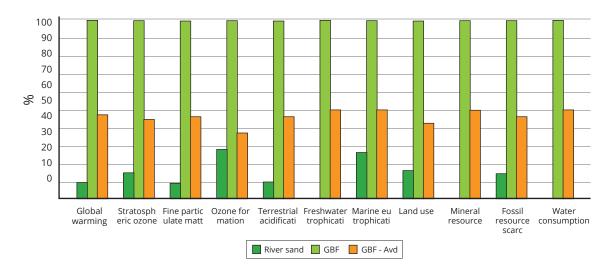
and conventional river sand, therefore, were kept separate in order to have a better understanding among other alternatives.

**Figure 23.** Life cycle impact analysis for different subbase layer mix-Avoidance Scenario (own illustration, SAND! Project)



In comparison with the normal scenario in avoidance scenario with the avoided process, the GBF slag layer showed about 50% reduction across all impact categories.

Figure 24. Life cycle impact analysis for different subbase layer mix—Avoidance Scenario (own illustration, SAND! Project)

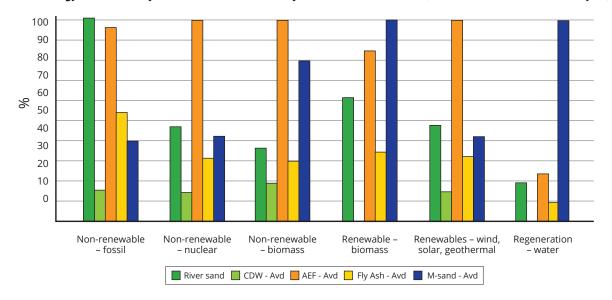


#### Energy demand analysis-avoidance scenario

Rather than the normal scenario, the alternative mixes in the avoidance scenario exhibited far better energy demand in non-renewable fossil sources. The conventional sand layer and alternative EAF layer had only a marginal difference in this scenario in the non-renewable fossil category. Overall, across all energy source categories, the energy demand remained high for the conventional mix layer (Figure 25). Among

the alternative mixes, the CDW layer utilises lesser energy with avoidance benefits. The energy demand reduction is about 80% compared to the conventional layer in the non-renewable fossil category. M-Sand has the highest energy demand in the renewable water category, similar to the normal scenario. Figure 26 shows that the GBF slag layer utilises 50% reduced energy in the avoidance scenario compared with a normal scenario. At the same time, the energy demand of the GBF slag layer remains higher than the conventional layer in this scenario.

Figure 25. Energy Demand Analysis for different subbase layer—Avoidance Scenario (own illustration, SAND! Project)



100 90 80 70 60 % 50 40 30 20 10 Non-renewable Non-renewable Non-renewable Renewable -Renewables - wind. Regeneration - fossil – nuclear - biomass biomass solar, geothermal

River sand GBF GBF - Avd

**Figure 26. Energy Demand Analysis for different subbase layer—Avoidance Scenario** (own illustration, SAND! Project)

#### 6.2.3 CONCLUSION

This study assessed the environmental impacts of utilising different alternative materials in road subbase layer applications. The study's results highlighted the better environmental footprints, especially in global warming and mineral resource scarcity impact categories of alternative materials in complete substitution. The LCA analysis results showed differences in the scenario analysis considering a normal scenario and avoided scenario.

- The results for the road subbase layer indicated that construction waste and fly ash carried a lower GWP, mineral resource scarcity and other footprints lower in normal scenarios within the alternatives. Further, on considering avoidance, the footprint of these materials reduces more. The GWP impact is reduced by 80% with construction waste, 13.2% with EAF slag, 55.8% with M-Sand and 47.9% with fly ash on considering avoided process benefits. With avoidance, except GBF slag, all the alternatives had a better impact footprint than the conventional subbase layer.
- The overall LCA analysis for the road subbase layer highlighted that the most footprint contribution was involved in the material transportation processes involved concerning construction materials. Thus,

- sourcing materials closer to the site or using low emission transport alternatives needed to be considered.
- The cumulative energy demand analysis highlights the need to shift from fossil-based to renewable energy sources, which could benefit the environment.

The use of secondary waste as alternative construction materials provides a significant environmental advantage. It reduces the quantity of virgin raw materials required and benefits the reduction in the number of waste materials disposed at landfills. Also, economically, the landfill disposal cost or transport cost of virgin materials from long-distances was reduced when utilising alternative materials. A major limitation in the study was the LCI data required for the modelling of the LCA. To a great extent, this limitation affected the representativeness of the LCA model to the region, and the results carry a high level of uncertainty. Currently, there is a significant lack of data relevant for this type of LCA study in Vietnam. The lack of quality data and covid-19 has placed a constraint on the LCI development. Therefore, the study relies hugely on the global database from Ecoinvent. The obtained results remain a general overview of the impact reduction advantages of using secondary waste materials as alternative substitutes in the road sub-base construction process

# 6.3 LCA ON LANDFILL CAPPING LAYERS UTILISING ALTERNATIVE AND WASTE MATERIALS

## 6.3.1 BACKGROUND AND FEASIBILITY ASSESSMENT: MINERAL SEALING LAYER LAB STUDY RESULTS

Owing to the increasing population and urbanisation, the municipal solid waste (MSW) volume is increasing. The MSW generation rate is estimated to rise annually by 10–16%, sources including households, restaurants, markets, municipal activities and businesses (Bui and

Nguyen, 2020), (Tong et al., 2021). Vietnam generates more than 27.8 million tons/year of waste from various sources such as municipal, agricultural and industrial waste (Schneider et al., 2017). According to Tsai et al. (2020), in municipal areas, the ratio of solid waste disposed of in landfills was approximately 34%, recycled waste accounts for approximately 42% and the remaining other disposal processes comprise about 24%. On average, Vietnam's waste generation was 0.7 kg/cap/day in urban areas and 0.4 kg/cap/day in rural areas (M., 2015). According to the World Bank (2018) about 63% of collected waste ends up in landfills and 22% goes to various treatment facilities. Vietnam has approximately 660 landfills, among which 204 were sanitary landfill and 456 were non-sanitary types. Table 8 elaborates on the distribution of landfills and their capacity across Vietnam.

**Table 8: Distribution of landfills and their capacity in Vietnam** (source: World Bank, 2018)

Landfills (LF)	Total LF	Sanitary LF	Non- Sanitary LF	Dumpsite waste received (t/year)	>20 hectare	1-20 hectare	<1 hectare
Western North	39	12	27	224.325	1	30	8
Western North	85	34	51	559.525	7	44	34
Economic Zone Northern	118	33	85	1.810.029	4	27	87
Economic Zone of Red River Delta	72	23	49	472.693	3	49	20
Economic Zone of Central	91	50	41	694.310	7	69	15
Economic Zone of Eastern South, Highland	113	21	92	1.008.488	5	81	27
Economic Zone of Southern	33	13	20	1.793.503	8	16	9
Mekong River	109	18	91	821.828	3	75	31
Total	660	204	456	7.384.701	38	391	231

Huge potential for landfill closure remains within Vietnam, requiring the consumption of vast natural resources like sand, clay and aggregates because of the current scenario of less aftercare of landfills in Vietnam. This scenario could be used to utilise secondary waste materials in the landfill closure construction process. Particular waste streams that could be involved in the landfill capping construction at various layers were a brick waste (BW), construction demolition waste (CDW), fly ash (FA), rice husk ash (RHA), glass waste (GW) and manufactured sand (m-sand/MS). For example, according to Hoang et al. (2020), waste brick with mortar and concrete waste forms a major share of about 51% of Vietnam's construction sector waste. These waste materials could be used as a partial or complete substitute for capping layers drainage, mineral sealing and recultivation. Since the costs for a modern installation of a conventional plastic liner might be of high economic value for the Vietnamese conditions, an alternative covering component would be a good choice. Among the waste base alternatives, it would be important to identify sustainable, low global-warming potential and environmentally low footprint carrying materials considering the climate change crises. Tables 9 -12 show the possible mixes of alternative waste



material layers considered for different landfill capping applications in this study.

The mix ratio for the conventional and alternative material-based drainage layer for this study is elaborated in Table 10. Alternative materials were made as a complete replacement for the conventional layer.

Table 9: Mix ratio of different materials for drainage layer used in the comparative study

Drainage Layer						
Conventional Layer	River sand					
Material	100%					
		M-sand	CDW	Crushed brick	Waste glass	
Alternative Layer		100%				
Material			100%			
				100%		
					100%	

The mix ratio for the conventional and alternative material-based mineral sealing layer is elaborated in Table 10. The alternative materials were made as a partial and complete replacement for the conventional layer in different mixes. The mineral sealing layer mixes using brick waste powder

were based on the scientific investigation water balance modelling (Schiffl, 2021). The mineral sealing layer mix utilising rice husk ash was based on a geotechnical lab report of ZAFT e.v HTW Dresden.

Table 10: Mix ratio of different materials for mineral sealing layer used in the comparative study

Lớp phủ bãi chôn lấp						
	Sét	Bentonite	Gạch phế thải	Tro bay	Tro vỏ trấu	Cát
Mix 1	97%	3%	-	-	-	-
Mix 2	47%	3%	50%	-	-	-
Mix 3	54%	1.5%	43%	-	-	1.5%
Mix 4	72%	1.5%	25%	-	-	1.5%
Mix 5	50%	-	-	50%	-	-
Mix 6	-	20%	-	80%	-	-
Mix 7	20%	20%	-	-	60%	-
Mix 8	60%	-	-	-	40%	-
Mix 9	60%		20%		20%	

The mix ratio for the conventional and alternative material-based mineral sealing layer is elaborated in Table 11. Alternative materials were made only as a partial replacement along with the conventional layer in different mixes.

Table 11: Mix ratio of different materials for recultivation layer used in the comparative study

Recultivation Layer						
Conventional Layer	Soil					
Material	100%					
	Soil	CDW	Crushed brick			
	70%	30%	-			
Alternative Layer Material	50%	50%	-			
	70%	-	30%			
	50%	-	50%			

Table 12: Different combinations of landfill capping layers used in the comparative study

	Conventional System	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6	Alternative 7	Alternative 8
Recultivation layer	Soil	Soil + Brick waste (50/50)							
Drainage layer	River sand	M-sand	M-sand	M-sand	M-sand	Glass waste	Glass waste	Glass waste	Glass waste
Mineral sealing layer	Mix 1 (table 3)	Mix 3 (table 3)	Mix 4 (table 3)	Mix 6 (table 3)	Mix 8 (table 3)	Mix 3 (table 3)	Mix 4 (table 3)	Mix 6 (table 3)	Mix 8 (table 3)

# 6.3.2 FEASIBILITY ANALYSIS: SOIL MECHANICAL TEST

The scope of the investigation was to identify feasible materials or material mixes that can be used as substitutive building materials for the sealing layer of the landfill capping system. Regarding the legal requirements for the landfill sealing layers, the demands of the German Landfill Act (Dep V, 2009) were considered, because that legislation provides clear instructions regarding the landfill layer systems. The Vietnamese norm "TCVN 6696:2009: Solid wastes—Sanitary landfill—General requirements for environmental protection" only contains general assumptions and requirements. More details are contained in the standard "TCXDVN 261:2001 Solid waste landfills—Design standard," however standard is also not very specific and does not have information about substitutive building materials. According to that legislation, landfills were divided into classes, depending on their hazard potential. Class I refers to "above-ground landfill for moderately contaminated excavated earth and rubble and comparable mineral commercial waste". Class II refers to waste with a higher level of pollutants that also has a higher biological content than that in landfill class I. Higher landfill classes refer to hazardous waste landfills that are in any case excluded from the implementation of substitutive building materials.

The key parameter for the assessment of leachate formation through a sealing system or component is the hydraulic conductivity of the sealing material. It describes the gravitational flow rate at which water seeps into the ground through interconnected voids of materials, described in hydrology through the permeability coefficient kf. The German legislation for surface sealing systems requires  $kf \le 5 \times 10-9$  m/s for landfill class I (simple landfills for construction rubble) and  $kf \le 5 \times 10-10$  m/s for class II (pretreated municipal waste landfill).

For the lab study, the selected materials were Asian rice husk ash and milled brick waste. Moreover, fly ash was taken into consideration as a potential sealing layer, based on wide relevance and usage among similar construction applications that had already proven the hydraulic conductivity of that material type. The mix ratio for the mineral sealing layer was elaborated in Tables 13 and 14. The alternative materials were made as a partial replacement for the conventional layer in different mixes.

Table 13: Mix ratio for milled brick (MB) used in lab testing

Mixture	Milled Brick (%)	Clay (%)	Fine sand (%)	Bentonite (%)
MB 1	43	54	1.5	1.5
MB 2	54	43	1.5	1.5
MB 3	50	50	-	-
MB 4	75	22	1.5	1.5
MB 5	25	72	1.5	1.5
MB 6	97	0	1.5	1.5

Table 14: Mix ratio for rice husk ash (RHA) used in lab testing

Mixture	RHA (%)	Milled Brick (%)	Clay (%)
RHA 0 (pure)	100	-	-
RHA 1	20	20	60
RHA 2	40	20	40
RHA 3	40	20	20
RHA 4	20	-	80
RHA 5	40	-	60
RHA 6	60	-	40
RHA 7	80	-	20

#### **6.3.3 SOIL MECHANICS RESULT**

The lab results for the potential sealing layer material indicated very low permeability values for some mixtures of about  $10^{-10}$  m/s that meet German quality requirements which require  $k \le 5 \times 10^{-9}$  m/s for landfill class I and  $k \le 5 \times 10^{-10}$  m/s for class II [54]. The interim conclusion was that one could add the rice husk ash and milled brick as substitutive materials up to 40 % of the sealing mix to reach the required hydraulic conductivities. The following soil mechanical parameters have been determined:

- w (-) water content
- ρs (g/cm³) installation density
- pPr (g/cm³) proctor density
- wPr (-) water content at proctor density
- kf (m/s) hydraulic permeability
- FC (%) usable field capacity
- AC (%) air capacity

The results in Table 15 show that mixes MB 2 and MB 3 were feasible material mixtures to reach the quality requirements for class II landfill mineral sealing systems. The mix MB 1 and MB 5 still reached the quality requirements for class

I landfill mineral sealing systems. Meanwhile the mixes MB 4 and MB 6 did not comply with quality requirements and remained unsuitable for sealing applications.

Table 15: Soil mechanical properties of the material mixtures with milled brick

Mixture	w (-)	ρs (g/cm³)	ρPr (g/cm³)	wPr (-)	kf (m/s)	FC (%])	AC (%)	Feasibility
MB 1	0.0072	2.709	1.826	0.1415	1.79 × 10 <sup>-10</sup>	22.61	4.93	Class II
MB 2	0.0072	2.709	1.791	0.1378	2.66 × 10 <sup>-9</sup>	28.74	5.64	Class I
MB 3	0.0065	2.718	1.799	0.1393	1.14 × 10 <sup>-9</sup>	26.30	5.77	Class I
MB 4	0.0058	2.711	1.744	0.1650	1.06 × 10 <sup>-8</sup>	38.09	5.32	Not Applicable
MB 5	0.0078	2.715	1.791	0.1422	1.71 × 10 <sup>-10</sup>	34.88	5.42	Class II
MB 6	0.0054	2.700	1.555	0.1891	3.69 × 10 <sup>-7</sup>	34.95	7.28	Not Applicable

The results in Table 16 show that mixtures RHA 1, RHA 3 and RHA 4 were feasible material mixtures to reach the quality requirements for class II landfill sealing systems. The mix RHA 2 values remained to be eligible for the quality requirements for class I landfill sealing systems. The mixes RHA 5, RHA 6 and RHA 7 did not comply with the

quality requirements. Further materials have been considered in the LCA study, particularly fly ash, which has already been proven in the past as a feasible substitutive building material for landfill sealing layers. Based on the pre-feasibility verification, the mix in Table 17 was adopted for further LCA assessment.

Table 16: Soil mechanical properties of the material mixtures with rice husk ash

Mixture	w (-)	ρs (g/cm³)	ρPr (g/cm³)	wPr (-)	kf (m/s)	FC (%])	AC (%)	Feasibility
RHA 0	0.1848	1.655	0.184	0	n.m.	7.64	60.50	Not Applicable
RHA 1	0.0081	2.598	1.500	0.2155	5.05 × 10 <sup>-10</sup>	22.70	9.35	Class II
RHA 2	0.0064	2.407	1.233	0.3125	$3.43 \times 10^{-9}$	20.87	17.16	Class I
RHA 3	0.0067	2.576	1.530	0.2065	3.56 × 10 <sup>-10</sup>	25.07	11.22	Class II
RHA 4	0.1043	2.187	1.076	0.3405	$4.47 \times 10^{-10}$	20.10	3.75	Class II
RHA 5	0.0824	2.179	0.864	0.5148	7.39 × 10 <sup>-9</sup>	26.97	10.61	Not Applicable
RHA 6	0.0968	2.175	0.998	0.4030	2.04 × 10 <sup>-8</sup>	29.11	16.67	Not Applicable
RHA 7	0.1756	1.764	n.m	n.m	1.22 × 10 <sup>-4</sup>	18.88	44.64	Not Applicable

Table 17: Mix ratio of the different materials for mineral sealing layer used in the comparative investigation

	Clay	Bentonite	Milled Brick	Fly Ash	Rice Husk Ash	Sand
Mix 1	97%	3%	-	-	-	-
Mix 2	47%	3%	50%	-	-	-
Mix 3	54%	1.5%	43%	-	-	1.5%
Mix 4	72%	1.5%	25%	-	-	1.5%
Mix 5	50%	-	-	50%	-	-
Mix 6	-	20%	-	80%	-	-
Mix 7	20%	20%	-	-	60%	-
Mix 8	60%	-	-	-	40%	-
Mix 9	60%		20%		20%	

#### **6.3.4 LIFE CYCLE ASSESSMENT**

This investigation involves the utilisation of the LCA tool to calculate and analyse the environmental impacts of different landfill capping layers individually and the overall cap using conventional and alternative waste materials relevant to Vietnam. The landfill capping layers in this comparative study involve the recultivation layer, mineral sealing layer and drainage layer. The table elaborates the capping layer along with their conventional material and alternative material composition. These alternative materials could be used to partially or completely replace conventional raw materials such as river sand, clay and soil in landfill capping applications. Using the LCA tool, the environmental footprints of the alternative waste-based layers were compared with each other and with the corresponding conventional layers. The primary goal of this

study was to evaluate the potential environmental benefits of using recycled materials and to determine which of the alternative mixes was relatively more or less sustainable. This study used transport distances from cradle to gate as 30 km for normal building materials and 65 km for ashes and slags based on information of the SAND! Project. The study also involves a scenario analysis, which considers two scenarios. The first scenario involves the avoided process caused through using alternative materials. In the avoided scenario, the benefits of avoided production of conventional materials, such as natural aggregate or sand in different layers and process specific burden involved in landfill disposal of the secondary waste, while using alternative subbase layers were considered. The second scenario is a comparison of conventional landfill capping system and landfill capping consisting of better alternatives than the normal scenario.

Table 18: Conventional and alternative materials involved in landfill capping layers

Landfill Capping Layers	Conventional Materials	Potential Alternative Materials
Recultivation Layer	Soil	Construction Demolition waste (CDW) Brick Waste (BW)
Mineral Sealing Layer	Clay and Bentonite	Rice Husk Ash (RHA) Brick Waste (BW) Construction Demolition Waste (CDW) Fly Ash (FA)
Drainage Layer	River Sand (RS) or Gravel (GR)	Construction and Demolition Waste (CDW) Brick Waste (BW) M-Sand or Crushed Sand (MS) Glass Waste (GW)

# 6.3.5 FUNCTIONAL UNIT AND SYSTEM DESCRIPTION

The functional unit for the landfill capping construction was the different landfill layers. The materials were primarily produced outside of the landfill area. The production of the materials occurs within the product system. The functional

unit for the study would be a one-hectare area of a landfill that requires a drainage layer for several variants of a mineral sealing layer to be replaced by alternative materials mix utilising fly ash, brick waste, rice husk ash, construction and demolition waste and brick waste. The basic functional unit was different landfill layers at a sample area of one hectare at their respective depth, as indicated in Table 19.

Table 19: Functional unit for different landfill capping layers used in the study

	Landfill Layers Functional Unit	
Landfill Sample Area	1 hectare / 10000 m <sup>2</sup>	Volume-based on Depth
Depth of Recultivation Layer	1m	10000 m³
Depth of Mineral Sealing Layer	0,6m	6000 m³
Depth of Drainage Layer	0,3m	3000 m³

In this LCA analysis, only the production stage involved in the supply of raw materials and alternative materials were considered. Therefore, this is called the cradle-to-gate approach. The onsite installation process, geosynthetic layer and service life of landfill capping layers in conventional or alternative caps are assumed to be similar, so

they were not considered in the analysis. The system boundaries for both conventional and alternative layer mixes include the production of raw materials such as the extraction of natural aggregates, their processing, waste processing and transport to the site.

#### **6.3.6 DRAINAGE LAYER**

The volume of materials required to fill 3000 m<sup>3</sup> of drainage layer of 0.3m thickness over a one-hectare area was estimated based on the density values from Table 20.

Table 20: Density of materials used in the drainage layer comparative LCA study

Materials	Density (t/m³)	
River Sand	2.60	(G.Singh and R.Siddique, 2012) (Kazi Aoual-Benslafa et al., 2014)
Gravel	1.80	(Frischknecht et al., 2011)
M-sand	2.65	(Shen et al., 2017)
Construction waste	1.95	(Ecoinvent)
Brick waste	2.00	(Kasinikota and Tripura, 2021)
Waste glass	2.60	

#### **6.3.7 MINERAL SEALING LAYER**

The volume of materials required to fill 6,000 m<sup>3</sup> of a mineral sealing layer of 0.6m thickness over a one-hectare area was estimated based on the density values from Table 21.

Table 21: Density of materials used in the mineral layer comparative LCA study

Materials	Density (t/m³)	Nguồn
Clay	1.76	(SIMETRIC, 2014)
Bentonite	1.50	(Kaufhold et al., 2013)
Brick Waste	2.00	(Kasinikota and Tripura, 2021)
Fly Ash (closely packed)	1.20	(Kantesaria et al., n.d.) (FARC and SPCB, 2015)
Rice Husk Ash	2.11	(Pode, 2016)

#### 6.3.8 LCA ANALYSIS

The LCA analysis involved comparing conventional mineral sealing layer mix 1 and alternative material layers (S1). The GWP impact results showed that all alternative mixes except mixes 6 and 7 had a lower impact than the conventional mix 1. The higher GWP impacts seen for mix 7, was greatly contributed to by the bentonite

material flow, as the mix had 20% bentonite, along with the 65km transport involved for ash. Mix 5 had the least GWP impact (107,984.38 kg CO2 eq), with 50% fly ash having zero allocation for its production and the only impact was from the 65km transport. The impact contribution was 62.7% from the transport process and 37.3% from clay extraction (Figure 27). The LCA analysis for the landfill capping layers highlighted that the

greatest environmental footprint contribution resulted from material transportation processes. Thus, sourcing of materials closer to the site is indicated, or using low emission transport alternatives need to be considered.

Similarly, mixes 2, 3 and 9 had a lower impact than the other alternatives and conventional mix 1, which could be directly associated with the reduced clay percentage in these mixes (Figure 27). The contribution analysis indicated that the mixes with an ash transport of 65 km had a transportation impact contribution of over 50% to 65%, while the mixes with regular materials

with 30 km transport had a 37–46% impact contribution from transportation (Figure 27). This higher contribution from the transportation process remains a concern in other similar studies. Mix 2 and mix 3, using brick waste in its composition, had approximately 10% lesser GWP impact than the conventional mineral mix 1. Within mix 2, 30.1% of the GWP impact arose from clay, 8.63% from bentonite processes, and 15.6% from brick waste processes. Meanwhile the composition of mix 3 had 34.80% GWP impact from clay processes, 4.34% from bentonite, 0.89% from sand and 13.5% from brick waste.

Figure 27: Mineral sealing layer—Contribution analysis for GWP impact category (own illustration, SAND! Project)

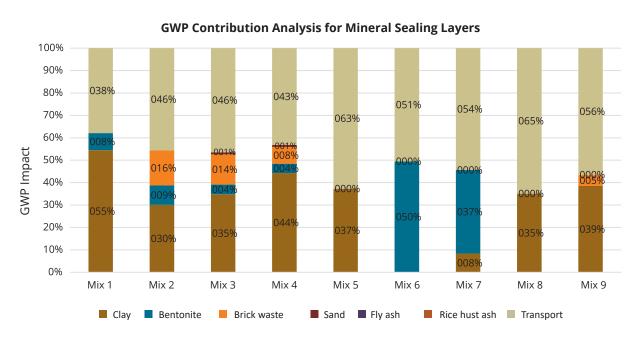
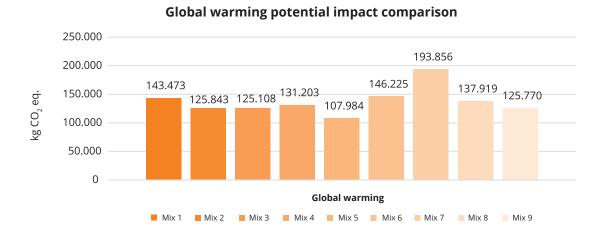


Figure 28: Global warming potential impact comparison between mineral sealing mix combinations (own illustration, SAND! Project)



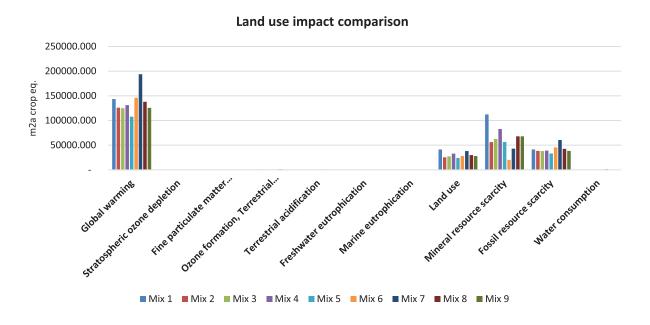
Overall, mixes 8 and 9, containing rice husk ash at 40% and 20%, respectively, carried an approximately 40% lower GWP impact footprint than the conventional mineral sealing layer (mix 1), while mix 2 has a 50% reduction. In the mineral resource impact category, mix 6 with fly ash at 80% had the smallest footprint, which was about 81.9% lower than mix 1. In general, all the alternative material-based mix layers possessed a lower mineral resource impact footprint than

the conventional layer mix (Figure 29). Apart from mix 4 and mix 7 among the proposed alternative mix layers, other mixes on average had 40% lower land use impact than mix 1 (Figure 30). The higher percentage of 72% clay in mix 4 and a higher percentage of 20% bentonite in mix 7 along with ash transport 65 km contributed to this increased impact.

Figure 29: Mineral resource scarcity impact comparison between mineral sealing mix combinations (own illustration, SAND! Project)

# Mineral resource scarcity impact comparison 250000.000 150000.000 50000.000 6ubota transition Cotone formation Terrestrial acute function Terrestrial acute functio

**Figure 30: Land use impact comparison between mineral sealing mix combinations** (own illustration, SAND! Project)

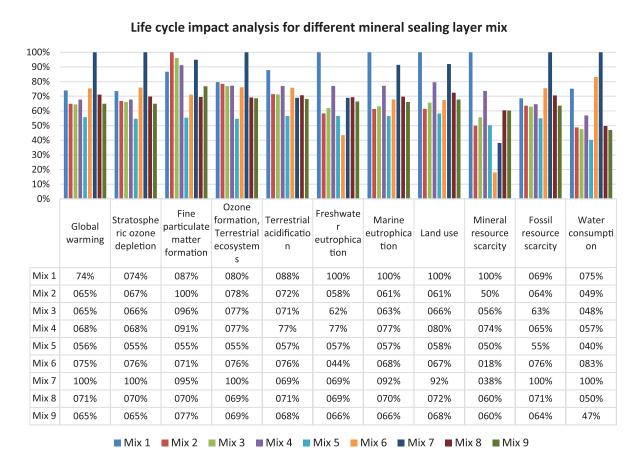


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The impact categories of acidification and eutrophication for the alternative layer mixes remained lower than the conventional mix 1 (Figure 28). Mix 7 posed higher impacts than the other proposed alternatives across categories-global warming potential, stratospheric ozone depletion, fossil resource scarcity and water consumption. This variation of mixes 6 and 7 was mainly contributed to by 20% bentonite

and the 65 km ash transport in the mix recipe. The alternative mixes, except mix 6 and mix 7, contributed 25% less water consumption impact than the conventional mineral sealing mix 1. Overall, the utilisation of the alternative materials demonstrated that reusing wastes can lead to a considerable reduction in environmental impacts caused by conventional materials, as commonly discussed in several types of research.

Figure 31: Life cycle impact analysis for different mineral sealing layer mix (own illustration, SAND! Project)



Mix 5 exhibited a lower energy demand in non-renewable fossil sources (coal), based on the considered unit processes from Ecoinvent, which was Vietnam's current scenario. Mix 5 had an energy reduction of approximately 45% compared with mix 7 and 15% reduction in comparison with conventional mix layer 1. The alternative mix 6 and mix 7 have higher energy consumption among the mixes in non-renewable fossil sources which were about 2,088,089 MJ and 2,764,583

MJ, respectively (Figure 29). All alternative mixes consume lesser energy in the renewable-based sources than conventional mix 1 (Annex), which showed that the benefits could be higher on moving towards complete renewable energy sources. The cumulative energy demand analysis highlights the need to shift from fossil-based to renewable energy sources, benefiting the environment.

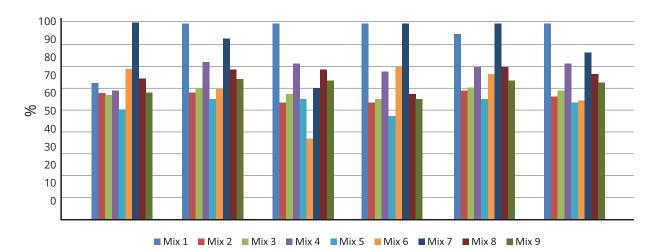


Figure 32: Energy Demand Analysis for different mineral sealing layer materials (own illustration, SAND! Project)

#### 6.3.9 CONCLUSION

This study assessed the environmental impacts of utilising different alternative materials in landfill capping layers such as drainage, mineral sealing and recultivation. The results of the study highlighted the improved environmental footprints, especially in global warming and mineral resource scarcity impact categories of alternative materials and their specified ratio in substitution. The LCA analysis results showed differences in the scenario analysis considering a normal scenario and avoided scenario.

- The results for the drainage layer indicated that brick waste and construction waste carry lower GWP, mineral resource scarcity and other footprints lower than in normal scenarios. Furthermore, on considering avoidance, the carbon footprint of these materials is reduced. The GWP impact reduces by 87% with brick waste, 80% with construction waste, 74% with glass waste and 52% with M-Sand on considering avoided process benefits.
- The results of the mineral sealing layer showed that higher bentonite composition of about 20% in the mix ratio and 65 km transport distance of ashes increases the overall footprint of the mix. In this case, mix 6 and mix 7 tend to possess higher impacts despite the alternative ashes holding zero allocation. The avoidance factor over the alternative mixes has an effective, about 25–50% GWP impact reduction. Therefore, except mix 6 and mix 7, other alternative materials look feasible, with brick waste mix showing a better performance in impact categories.

- The recultivation layer LCA analysis results for the alternative materials substitution at 30% and 50% ratio had a higher impact footprint than the conventional topsoil layer. The avoidance benefit consideration only reduces the difference marginally and the conventional layer only had a higher impact in the land use category, where alternative material substitution had 75% reduction in land use impact.
- The LCA analysis for the landfill capping layers highlighted that the greatest footprint contribution concerned the material transportation processes involved, regarding construction materials. Thus, sourcing of materials closer to the site or using low emission transport alternatives needs to be considered.
- Overall, landfill capping systems utilising various alternative combinations indicated that with the avoided benefits in avoidance scenario, the combination system by using glass waste and brick waste had a better environmental footprint across the 4 main impact categories GWP, mineral resource, land use and water consumption. Combination 1 also had a better footprint except regarding the water consumption impact category. In the normal scenario without avoided impacts, the combination 1 using brick waste and M-Sand as alternatives indicated a better footprint across 3 impact categories GWP, mineral resource and land use. In the normal scenario, other capping systems had better footprints in only 1 or 2 impact categories.

The cumulative energy demand analysis highlights the need to shift from fossilbased to renewable energy sources, thus benefiting the environment.

The use of secondary waste as an alternative construction material provides a significant environmental advantage. It reduces the quantity of virgin raw materials required and benefits the reduction in the quantity of waste materials disposed at landfills. Also, economically, the landfill disposal cost or transport cost of virgin materials from long-distance were reduced on utilising alternative materials. A major limitation in the study was the LCI data required for the modelling of the LCA. To a great extent, this limitation affected the representativeness of the LCA model to the region, and the results unfortunately have a high level of uncertainty. Currently, there is a great lack of data relevant for this type of LCA study in Vietnam.

# 6.4 LCA ON NON-REINFORCED CONCRETE C25/30 USING ALTERNATIVE CEMENT MATERIALS

# 6.4.1 ASSESSMENT OF FEASIBILITY: CONCRETE LAB STUDY RESULTS

The concrete test specimens were produced according to the formulations of strength class C 25/30 in accordance with DIN EN 206. For the calculation of the formulations, the grain density of the aggregates was determined according to DIN EN ISO 17892-3. A Portland cement CEM II/A-LL 32.5 R was used. The base formulation C 25/30 concrete was replaced by 10%, 20% and 30% ash for the cement (Table 22). The replacement was carried out using five different ashes: coarse Vietnam ash, filter ash, blast furnace ash (two types) and rice husk ash (Ash 5). The rice husk ash was crushed in a ball mill due to its coarser grain size. The concrete samples with ashes used crushed quartz as aggregate.

Table 22: Mix recipe used for the study

Materials		Control	10% Ash	20% Ash	30% Ash
Cement	[kg]	463	417	370	324
Ash	[kg]	0	46	93	139
Aggregate	[kg]	1627	1627	1627	1627
Water	[1]	232	232	232	232

The mixes with ash 2 (filter ash) and ash 5 (rice husk ash) have significantly lower values than other mixes and are therefore not suitable for the reduction of cement. The compressive strength results of mixes indicate that a higher proportion of ash reduces the compressive strength. Compressive strength values corresponding to the mixes with 10% for ash 1 (coarse ash) and ash

3 (BFA 1) exhibited strength equivalent to C25/30. The mixes with 10 % ash show higher strengths than mixes with 20% or 30 % ash replacement. Based on these results, a life cycle assessment for concrete of volume 1m3 based on the mix using 10% coarse ash and blast furnace ash is performed to understand the environmental footprint of alternative material-based concrete.

Figure 33: Laboratory analysis on strength properties of concrete mixes (photo credit: C&E GmbH)







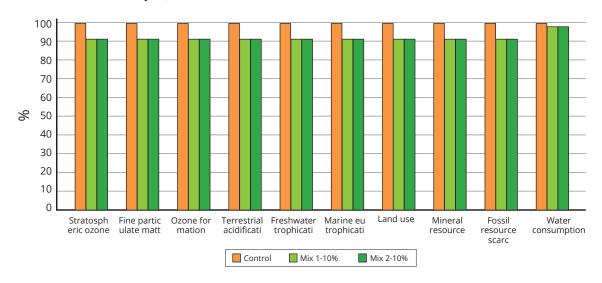
#### 6.4.2 LIFE CYCLE ASSESSMENT

This study involves the utilisation of the LCA tool to calculate and analyse the environmental impacts of non-reinforced concrete of strength C25/30 using conventional and alternative waste materials to replace cement with relevance to Vietnam. The table elaborates on different concrete sample compositions. All these alternative materials can completely replace conventional cement in concrete application. Using the LCA tool, the environmental footprints of the alternative waste-based concrete were compared with each other and with the corresponding conventional concrete. The primary goal of this study was to evaluate the potential environmental benefits of using recycled materials and determine which of the alternative mixes were relatively more or less sustainable. The assessment used transport distances from cradle to gate as 30 km for normal building materials and 65 km for ashes based on information from Vietnamese partners.

#### **6.4.3 LIFE CYCLE ASSESSMENT RESULTS**

The LCA study results for the non-reinforced concrete of strength C25 involving conventional cement and alternative materials compared and interpreted. Note that only the materials production or recycle process and their transportation to site impacts were reflected in the LCA calculations. The cement replacement of 10% with ash indicates a reduction of global warming potential (GWP) of about 38 kg per m3 of concrete for both the mixes. It ought to be noted that the ash carries a zero-allocation considered as waste and therefore the reduction is directly contributed from 10% cement reduction. The GWP potential of the control sample recipe was 400 kg CO<sub>2</sub> eq while the alternatives mixes had 362 kg CO<sub>2</sub> eq.

Figure 34. Comparison of life cycle assessment of concrete samples across different impact categories (own illustration, SAND! Project)



The cement contributes the highest share of GWP at about 95%. The remaining contribution arises from sand/aggregate with about 1.5% and transportation processes contributing 3.17–2.71%. The alternative material utilisation shows a reduction in mineral resource scarcity impact, highlighting a further possibility to research and improve the secondary waste material utilisation in construction application at higher percentages. Overall, the alternative mixes exhibit an average 10% reduction among all the

impact categories except water consumption. In the water consumption category, the reduction of impact is only marginal at around 2% and describes the different sources of energy demand involved within the life cycle of the concrete mixes. The alternative mixes have a 10% reduced energy consumption across the different energy sources (Figure 35). There is a large scope to shift the energy source to 100% renewable-based to attain decarbonisation in the value chain.

100 90 80 70 60 % 50 40 30 20 10 0 Renewables - wind, Non-renewable Non-renewable Non-renewable Renewable Regeneration fossil nuclear biomass biomass solar, geothermal water Control Mix 1-10% Mix 2-10%

Figure 35. Energy demand analysis within the life cycle of the concrete mixes (own illustration, SAND! Project)

#### 6.4.4 CONCLUSION

This study assessed the environmental impacts of utilising ash-based alternative materials in the concrete application for replacing the cement consumption. The results of the study highlighted the improved environmental footprints across impact categories with 10% substitution. The GWP impact reduction per cubic meter of concrete was 38 kg, which, on larger consumption, contributes to an emission reduction. The LCA analysis results showed that cement as a component in concrete holds the highest impact footprint. Therefore, it is necessary to consider alternative materials with lower environmental footprints to replace cement or technological improvements along the cement value chain to lower the product footprint, as it is a widely used construction material. The LCA study also indicates the need for shifting the energy sources from fossil-based in the construction value chain to low carbon or emission-based renewable sources to attain the global net-zero targets.

The use of secondary waste as alternative construction materials provides a significant environmental advantage. It reduces the quantity of virgin raw materials required and benefits

the reduction in the number of waste materials disposed at landfills. Also, economically, the landfill disposal cost or transport cost of virgin materials from a long-distance were reduced on utilising alternative materials. Despite the impact reduction, the utilisation of fly ash still requires quality checks in terms of their hazardous nature with heavy metals presence, as all fly ashes are not suitable for practical replacement considering their pollutant load level and permissible standard regulation from the government body. A prior chemical analysis must be carried out before utilising ashes within the construction application to understand their leaching properties over a longer time period. A major limitation in the study was the LCI data required for the modelling of the LCA. To a great extent, this limitation affected the representativeness of the LCA model to the region, and the results therefore have a high level of uncertainty. Currently, there is a great lack of data relevant for this type of LCA study in Vietnam. Therefore, the study relies hugely on the global database from Ecoinvent. The obtained results remain a general overview of the impact reduction advantages of using secondary waste materials as an alternative cement substitute in non-reinforced concrete.

# 6.5 LCA ON NON-REINFORCED CONCRETE C25/30 USING DIFFERENT AGGREGATES

# 6.5.1 ASSESSMENT OF PREFEASIBILITY: CONCRETE LAB STUDY RESULTS

The concrete test samples are produced according to the formulations of strength class C 25/30 in accordance with DIN EN 206. For the calculation of the formulations, the grain density of the aggregates was determined according to DIN EN ISO 17892-3. Portland cement CEM II/A-LL 32.5 R was used. The base formulation C 25/30 concrete was replaced with different aggregates based on basalt, granite, marble, amphibolite, brick waste and quartz (Table 23).

Table 23: Mix recipe used for the investigation

Materials		Quartz Broken Flaky	Quartz Round, Granule	Marble	Amphibolite	Basalt	Granite	Quartz flaky + waste ( vol	Brick (50/50
Cement	[kg]	463	415	488	369	409	383	36	55
Aggregate	[kg]	1627	1735	1652	1998	2054	1947	896	921
Water	[l]	232	207	244	185	204	192	18	32

The results indicated that the concrete cubes containing basalt, quartz, marble and granite aggregates had the compressive strength at the C 25/30 standard requirement. While the concrete cubes with amphibolite and brick waste failed in the compressive strength test. The angular grains of the crushed materials do not seem to have a significant negative influence on the strength and the results are comparable to river sand with a round grain shape. The flaky grain shape of the metamorphic amphibolite leads to a significant reduction in strength. Brick rubble absorbs a large amount of water and has a negative effect on strength. Based on these results, a life cycle assessment for concrete of volume 1m3 based on the mix using 100% aggregates of crushed basalt, crushed quartz, rounded quartz, crushed granite and crushed marble were performed to understand the environmental footprint of alternative sand-based concrete.

#### 6.5.2 LIFE CYCLE ASSESSMENT

This investigation involves the utilisation of the LCA tool to calculate and analyse the environmental impacts of non-reinforced concrete of strength C25/30 using different aggregates with relevance

to Vietnam. Table 25 elaborates on different concrete sample compositions. All these aggregate materials can completely replace conventional river sand in concrete applications. Using the LCA tool, the environmental footprints of the studied concrete were compared with each other. The system boundary considered was cradle to gate, where only material production and transportation to the site was considered. This study uses transport distances from cradle to gate as 30 km for traditional building materials based on information from Vietnamese partners.

# 6.5.3 FUNCTIONAL UNIT AND SYSTEM DESCRIPTION

The functional unit for this investigation was the non-reinforced concrete sample of strength C25/30, where the materials were primarily produced outside of the construction area. The production of the materials comes within the product system. The functional unit for the investigation was a 1m3 of concrete at strength C25 using different aggregates. Table 24 elaborates the recipe of the functional unit considered.

Table 24: Concrete recipe for the functional unit 1m<sup>3</sup>

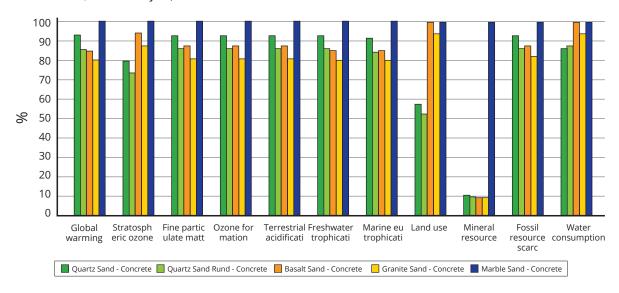
Materials		Quartz Broken Flaky	Quartz Round, Granule	Marble	Basalt	Granite
Cement	[kg]	463	415	488	409	383
Aggregate	[kg]	1627	1735	1652	2054	1947
Water	[1]	232	207	244	204	192

#### **6.5.4 LIFE CYCLE ASSESSMENT RESULTS**

The LCA investigation results for the nonreinforced concrete of strength C25 involving conventional cement and alternative materials were compared and interpreted. Note that only the materials production or recycle process and their transportation to site impacts were reflected in the LCA calculations. Among the different aggregate usage in the concrete, granite-based concrete has the least impact with 346 kg CO2 eq per m3 of concrete. The granite-based concrete has a 20% lower GWP impact than marble-based concrete (Figure 34). The basalt concrete and crushed rounded quartz concrete has a 15% lower GWP impact than marble concrete. The cement contributes the highest share of GWP at about 95%. The remaining contribution arises from aggregate about 1.4-2.18% and transportation processes contributing 2.68–3.54%. The variation in the GWP

contribution from aggregates was directly related to their mass present within the concrete mixes. Among the aggregates, the marble concrete utilising limestone-based unit process indicated higher mineral resource scarcity. This could be based on the characterisation values associated with limestone and the absence of such factors for other raw materials quartz, basalt and granite. In general, the granite aggregate concrete had a lower mineral resource scarcity footprint of 3.73 kg Cu eq. The land use impact footprint remains low for quartz-based aggregate concrete, which was about 50-55% lower than other aggregate concretes. The water consumption impact remains marginally close for all the concrete samples ranging from 3.12-3.64 m3 with granite aggregate concrete having a higher value. Marble concrete tends to have a bigger footprint in acidification, eutrophication and fossil resource scarcity impacts.

Figure 36. Comparison of life cycle assessment of concrete samples across different impact categories (own illustration, SAND! Project)



The granite aggregate concrete has lower energy demand than other mixes across all the energy source categories (Figure 37). The energy demand reduction for basalt, quartz and granite aggregate-based concretes varies between 7–18 % than the

marble aggregate concrete and was the same across all categories. There is a large scope to shift the energy source to 100% renewable-based to attain decarbonisation in the value chain.

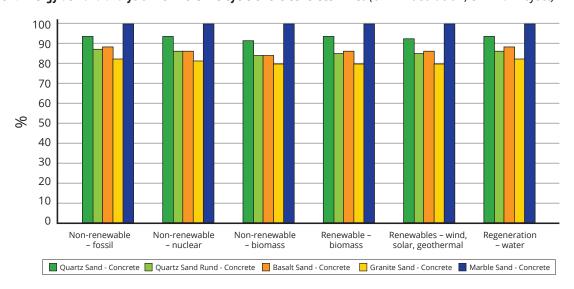
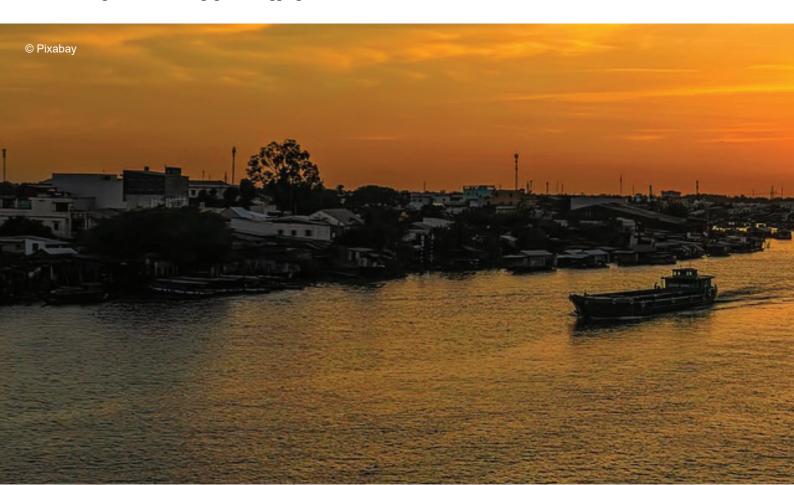


Figure 37. Energy demand analysis within the life cycle of the concrete mixes (own illustration, SAND! Project)

#### 6.5.5 CONCLUSION

This study assessed the environmental impacts of utilising different aggregate materials in the concrete application. The results of the study highlighted the improved environmental footprints across impact categories in utilising granite aggregate concrete.

Despite lower granite aggregate values, all the aggregates in general only had marginal differences in the impact footprint. Therefore, on considering the uncertainty on the concrete mix analysis in this study, other aggregates can also be considered for sustainable consumption. The LCA analysis results showed that cement as a component in concrete



holds the highest impact footprint. Therefore, it is necessary to consider alternative materials with lower environmental footprints to replace cement or technological improvements along the cement value chain to lower the product footprint, as it is a widely used construction material. The LCA study also indicates the need for shifting the energy sources from fossil-based in the construction value chain to low carbon or emission-based renewable sources to attain global net-zero targets.

#### **6.6 OVERALL LCA CONCLUSIONS**

The developed inventory of scientifically feasible secondary waste materials such as industrial and agricultural waste that can substitute sand and other construction fine aggregates either fully or partially in different construction applications such as concrete, bricks, etc. helps to identify a further application of feasible materials on market scale and the development of a Vietnamese quality framework for construction materials. The use of secondary raw materials as alternative fine aggregate construction materials provides significant environmental advantages. It reduces the quantity of primary raw materials required and benefits the reduction in the quantity of waste materials disposed at landfills. Also, economically, the landfill disposal cost or transport cost of primary materials from long-distance transportation was reduced on utilising alternative materials. Waste materials such as brick waste, rice husk ash, fly ash and construction demolition waste showed a better sustainability footprint in the varied applications.

The results of the impact assessment show that there is a close connection between the transport costs of the building materials and their life cycle assessments in the examined scope of investigation. In the case of long transport routes, the influence on the impact categories is particularly high. As a result, building materials have a better ecological balance if their raw materials come from regional sources. Furthermore, it was found that with the same transport costs, the primary raw materials sometimes have more positive values than substitute building materials when considering individual impact categories. On the one hand, this can be explained by less complex extraction methods, such as with lava and pumice. In contrast, the processing of, for example, concrete recycling or household waste incineration bottom ash is to be rated as more resource- and energy-intensive. At the same time, it is also evident that a significantly greater effort is required to excavate hard rock. This is also reflected in the results of the life cycle assessment. The higher the raw density of the material, the greater the use of energy and resources for mining.





## **SUMMARY**

After water, sand and clay are important resources in modern societies, as these materials form the main infrastructure building material resource. Having in view the global building material scarcity that is caused by the rapid consumption of primary natural mineral resources, there is a need to fill this gap. One way is the use of secondary building materials made from waste. The developed inventory of scientifically feasible secondary waste materials such as industrial and agricultural waste that can substitute

sand and other construction fine aggregates either fully or partially in different construction applications such as concrete, bricks, etc. aids the identification of further potential applications of feasible secondary materials on market scale and the development of a Vietnamese quality framework for construction materials. The findings are summarised in the table below. Primary replacement materials are usually used by 100% to produce M-Sand.

Table 25: Overview on conventional sand applications, alternative secondary materials as well as possible replacement percentage (own illustration, SAND! Project)

Conventional SAND Application	Alternative Materials	Possible Replacement Percentage	Additional processing required
Conventional Concrete	Rice Husk Ash	30%	
	Foundry Sand	20–30%	
	Sugarcane Baggase Ash	20–30%	
	Copper Slag	50%	(also ideal for pavement quality)
	Granulated Blast furnace slag	40–60%	
	Coal Bottom Ash	30–50%	
	Fly Ash	50%	
	Geopolymer fly ash sand	100%	
	Quarry Dust	50%	
	Granite Dust	30%	Trung bình
	Marble powder	10%	
	Waste Glass	10–20%	
	Foundry Slag	25%	
	Rubber Waste	7.5–25%	

Conventional SAND Application	Alternative Materials	Possible Replacement Percentage	Additional processing required
	Rice Husk Ash	30%	
Bricks	Flyash + Bottom ash	30%	
	Quarry dust	100%	
	Foundry Sand	30%	48mPa
	Sugarcane Bagasse Ash	20%	
Self-Compacting Concrete	Waste Glass	5–15%	
Contract	Foundry Slag	25%	
	RHA	25%	
	Copper Slag	40%	
High Strength Concrete	Quarry Dust	20%	
nigii saciigii concrete	Rubber Waste	30%	Ideal: seawater, har- bour-based application
	Coal Bottom Ash	100%	
	Fly ash	30%	1:4:8 / 1:2:4
Paving Blocks,	Quarry dust	30%	
Pavements, concrete blocks	Waste Glass	70%	cullet
DIUCKS	Rubber Waste	12.5%	pavements, floors and concrete highways, tunnels and dam spillways with NaOh 25%
	Fly ash	60–70%	
Mortar	Marble powder	20%	
	Waste Glass	20%	
Landfill Capping Layers	Rice husk ash	50–60%	
	Glass waste	100%	
	Brick waste	50–100%	
	Fly ash	50–80%	
	Construction waste	50–100%	

Conventional SAND Application	Alternative Materials	Possible Replacement Percentage	Additional processing required
Road Subbase	EAF Slag	100%	
	Blast furnace slag	100%	
	Construction waste	100%	
	Foundry sand	50-100%	

The use of secondary raw materials as alternative fine aggregate construction materials provides significant environmental advantages. It reduces the quantity of primary raw materials required and benefits the reduction in the quantity of waste materials disposed at landfills. Also, economically, the landfill disposal cost or transport cost of primary materials from long-distance transportation was reduced when utilising alternative materials. Waste materials such as brick waste, rice husk ash, fly ash and construction demolition waste showed a better sustainability footprint in the varied applications. Despite new developments in Vietnam for the topic of life cycle assessment, the construction sector authorities and stakeholders should foster life cycle relevant database development for various construction materials on national and regional levels, which could support the construction sector in adopting a sustainable pathway in the future. The obtained results remain a general overview of the impact reduction advantages of using secondary raw materials as an alternative to fine aggregate substitutes in the landfill capping, road subbase and concrete applications. To be able to fully benefit from the regional economic potential, to allowfor current activities to continue undisturbed, it is important to carry out construction materials mining, processing and utilisation of alternative materials in a responsible manner contributing to a "circular economy".



## OUTLOOK

Based on the findings of the assignment, the following needs were concluded:

**Improving Information Resource About Construction Materials Demand by Evidence-Based Methods.** To carry out planning for responsible mining of construction materials, an accurate estimation of the long-term supply and demand for these materials has to be made by the authorities. Without this important resource information, it is impossible to plan for sustainable consumption in the long-term.

**Promoting Responsible Consumption and Secondary and Renewable Raw Materials for Construction along with their Relevant Quality Requirements Development.** The shortage of river sand and several other construction materials based on the increasing demand will affect the construction industry greatly. Due to this, several kinds of research havebeen undertaken for easy and cheap available alternative waste materials to replace sand or several other fine aggregate materials completely or partially. In the first step, this key issue addresses a need for policy development and the setting of political targets as was outlined in the Government Decree 09/2021/ND-CP of February 9, 2021 on the management of building materials and the Strategy for the development of building materials in Vietnam for the period 2021–2030 with a vision until 2050. Having this framework, technical and quality norms should be developed and aligned with international rules. The private sector may support the industrial norm development to create the market for substitutive building materials. Ideas might be used from the German Circular Economy legislation (Kreislaufwirtschaftsgesetz), particularly the requirements for "end of waste status" ("Ende der

Identifying the Causes and Mitigation with Appropriate Responses for Delta Environmental Damage. Mining activities for construction materials result in several environmental and social consequences. The risk of contamination of the air, soil, groundwater and surface water often becomes a reality and plays a role in land-use conflicts, particularly when mining activities are located near settlements and agricultural areas. The demand for construction materials also causes resource depletion of existing supplies. The extraction of sand has effects directly and indirectly on the river/lake/ocean ecosystem and human health, despite the need for development.

Abfalleigenschaft"). Financial support for further R&D should be provided, for instance for quality norm

development for substitutive building materials as such, and in particular, in landfill construction.

**Capacity of Public Authorities.** Mineral products are essential for constructing modern societies and economies. To meet the demands for construction materials, extensive mining does not comply, rather ensuring natural environment protection and preservation is needed. The construction sector has many stakeholders. All stakeholders involved such as the provincial and local authorities, the mining industry, and the local population, must recognise that multiple interests exist. Subsequently, each entity must learn to pursue its own objectives in ways that move society, and thus the interests of all entities, forward as a whole.

Focus to Decarbonise the Energy Grid to Reduce Carbon Intensity Across the Value Chain. The study highlighted that the construction applications along their value chain involving construction materials extraction and transportation concerning Vietnam have a highly intensive fossil-based energy demand. Therefore, a focus on decarbonising the energy grid in future holds a key in attaining net-zero emissions in the coming years for Vietnam. A shift to increasing renewable-based energy, could reduce the carbon footprint involved in the construction materials extraction and also within its value chain and also benefits electric mobility-based transportation.

**Considering Switching to Environmentally Friendly Transportation for Construction Materials.** The transportation of construction materials causes a substantial contribution of environmental and cost footprint within the construction activity lifecycle. Therefore, it is important to have an optimised transportation distance and transport mode for construction materials.

Further Developing National and Regional Specific Lifecycle Inventory Data for the Construction Sector. LCA is a beneficial tool to identify the environmental burden of various products along its value chain. The analysis helps to assess the negative impacts of inputs and outputs within the value chain on long-term sustainability and develop mitigation efforts to reduce the impacts across various points of the product lifecycle. The LCA benefits manufacturers to reduce the impact of their products, policymakers to plan strategic climate goal policies and consumers to be aware of the context of sustainable products. The Vietnam Green Building Council (VGBC)—Green Database (database for the environmental assessment of building materials to identify building materials with lower environmental impact) could be used as a starting point.



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