# Novel Construction Materials for a Sustainable Future

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## Summary

In Singapore every year, hundreds of thousands of tons of industrial wastes and dredged material are being produced and disposed off. On the other hand Singapore has limited resources and imports all the essential raw materials needed for building and construction purposes. Since technologies are available to convert these wastes into potential materials applicable for the industry, it is worthwhile for Singapore to explore this option.

The Center for Sustainable Buildings and Construction (CSBC) of Building and Construction Authority (BCA) is working with NewEarth Pte Ltd, a local private enterprise to explore technologies to convert wastes like dredged material and spent copper slag to produce synthetic or engineered aggregates for building and construction applications. This is in line with the BCA's Sustainable Construction Masterplan (SCMP) to reduce and recycle wastes.

Under the SCMP, crushed concrete waste which is currently being used for lower value applications like backfilling and construction of temporary site access roads, will be 'up-cycled' and processed into recycled concrete aggregates used for structural applications. Alternative potential waste materials like dredged material and spent copper slag would thus be explored for lower-value usage or other civil engineering applications, which will in turn free up precious natural raw materials like granite for structural building works.

CSBC collaborated with NewEarth to use Crystallisation Technology to transform the mixed wastes of dredged material and spent copper slag into synthetic aggregates for this study. This is a patented technology comprising three key processes- Stabilisation, Fixation and Encapsulation, as well as Vitrification.

The study explores the use of these synthetic aggregates for replacement of coarse aggregates in concrete. In the design optimisation stage, various proportions of dredged material were used to produce the synthetic aggregates. They were sintered at various high temperatures and the performance of the synthetic aggregates was studied. Eventually aggregates with 50% dredged material sintered at 1000ºC were selected to produce the synthetic aggregate mix and used for further tests. Laboratory results indicated that the selected aggregate mix gave an impact value of 51% and water absorption of 5.24%. They also had a bulk density of less than 1200kg/m$^3$ and were therefore classified as lightweight aggregates. When these aggregates were used for the production of Grade 35 and Grade 40 concrete, results showed that the compressive strengths of both grades of concrete were satisfactory. For the next phase of the study actual field tests on the concrete produced with synthetic aggregates would be carried out.

In terms of environment impact, leaching test results showed that the concentration of toxic elements (heavy metals) leaching out from the synthetic aggregates did not pose any hazards to the environment and are therefore safe for building and construction applications.

The success of the project will go a long way towards contributing to Singapore's vision of achieving zero landfill.  It will also help reduce our over-reliance of imported building and construction materials.

# 1. Introduction

Singapore is a resource-challenged country. All our essential raw materials needed for the building and construction industry are imported. Because of our over-reliance on imported raw materials, uncertainty in the supply of these materials and the influence of global market forces can have a significant impact on our building and construction industry.

With advance in technology many types of wastes could be converted into useful products for the building and construction industry. Since natural resources are depleting and more alternative materials can be made available through technological means, it is timely and worthwhile to explore the use of such materials in construction works.

In Singapore every year, hundreds of thousands of tons of industrial wastes and dredged material are being produced. If these materials cannot be used in a meaningful way, they would have to be disposed off at our only offshore landfill site at Pulau Semakau. This practice is not only environmentally unfriendly; we are also shortening the lifespan of our remaining landfill site. On the other hand if there are suitable technologies to convert these materials into novel building and construction materials, the potential benefits and impact to the industry would be tremendous.

The Center for Sustainable Buildings and Construction (CSBC) of Building and Construction Authority (BCA) partnered NewEarth Pte Ltd, a local private enterprise to explore technologies to convert mixed waste of dredged material and spent copper slag to produce synthetic or engineered aggregates for building and construction applications.

Dredged materials are generated mainly from the dredging and excavation activities related to the construction and the maintenance of channels at the port terminals. They are sediments excavated under water, composing of alluvial deposits i.e., boulder, sand and mud, of which may contain toxic chemicals from land-based sources. Some level of contamination is inevitable and may vary depending on the proximity of human activities to the proposed dredging works. The commonly found contaminants include organic contaminants and heavy metals. The key challenge for the use of dredged materials is to decontaminate or stabilise the chemical contamination within the sediment matrix as well as to contain the toxic heavy metals present from leaching out.

Spent copper slag is the by-product generated from grit blasting works at the shipyards. It is basically inert with no apparent odour and irregularly shaped. Copper slag which itself is a by-product formed from the copper smelting process, is imported by our shipyards for grit-blasting to remove rust and marine deposits accumulated on the ships. Spent copper slag may be contaminated with rust and paints and becomes a waste material, however the contaminants can be easily removed.

# 2. BCA's Sustainable Construction Masterplan

Singapore realised that a whole-of-government approach is required to steer the whole country towards environmental consciousness. For this reason an Inter-ministerial Committee on Sustainable Development (IMCSD) was established and the Sustainable Blueprint was formulated. In a nutshell, IMCSD's goals are to improve resource efficiency and to achieve zero landfill.

In June 2009, BCA revised our Sustainable Construction Masterplan (SCMP) to be in line with IMCSD's goals. BCA champions the SC drive to lead the industry into the emerging paradigm of "Sustainability Development". SC is strategically critical to Singapore in 2 ways:

- Firstly, it mitigates impact on our limited landfill capacity and
- Secondly, it helps to reduce our dependence on imported construction materials and enhance our supply resilience for these materials.

Under this Masterplan, BCA aims to reduce the use of natural aggregates in concreting works for buildings through *recycling and use of recycled materials, while at the same time advocating the efficient use of natural materials, through for example design optimisation.*

To achieve these goals require a mindset change to view every waste as a potential resource for the next process in the construction value chain. Through the Masterplan, BCA will 'up-cycle' the majority of the concrete waste for higher-value applications, namely processing it into recycled concrete aggregates (RCA) for structural concrete in building works (Refer to Figure 1). Currently the bulk of crushed concrete has been used for lower value applications such as backfilling or as hardcore material for construction of temporary site access roads. At the same time BCA will also explore the use of potential waste materials as alternatives for lower value usage or other civil engineering applications. Dredged material and copper slag are some examples because of the substantial quantity generated. Modified dredged materials could also gradually replace traditional imported materials such as granite for non-structural concrete, thus freeing up more granite for structural building works.

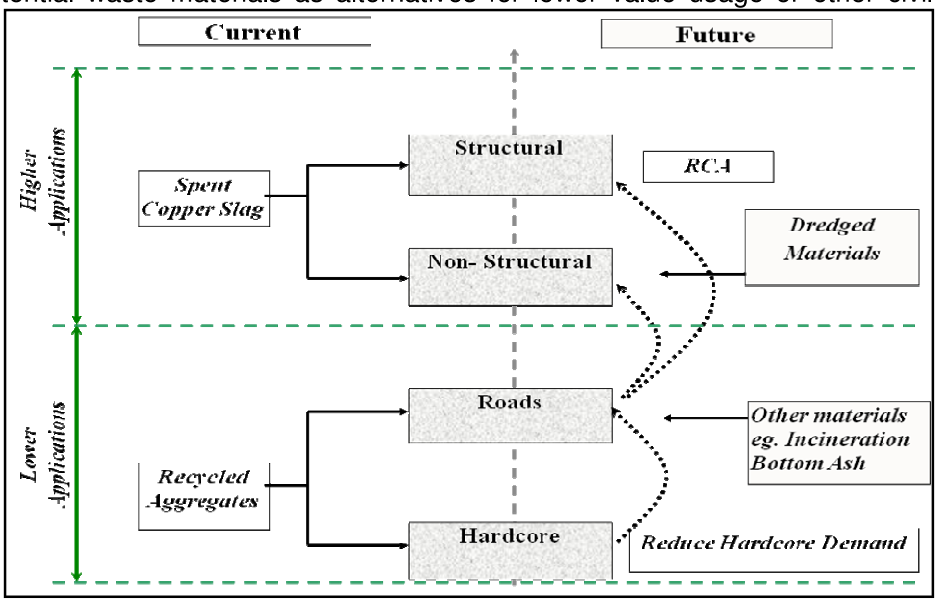



*Figure 1. Upcycling chart for building and construction materials*

## 3. Technology Developed to Treat Dredged Materials

Many studies have been carried out on the use of dredged materials for innovative construction applications. The production of aggregates for concrete from wastes is being recognized as a great potential for the utilization of large quantities of waste materials and this possibility has received increasing attention in recent years.

CSBC collaborated with NewEarth Pte Ltd on a research project to explore the use of synthetic aggregates converted from a mix of contaminated dredged material and spent copper slag for use in concrete. The initial research focus was to look at processes to treat sediments in the dredged material to render them suitable for varieties of beneficial uses. However it was found that very few processes have been developed to reduce, separate, immobilize or detoxify contaminants in the dredged materials.

By using intense heat to treat materials such as dredged material, high thermal ceramic aggregates are formed. Bhatty et al. [1] reported that sludge ash pellets sintered at an elevated temperature of 1050 deg C developed inert aggregate of reasonable strength, satisfactory for use as regular coarse aggregates in concrete. Tay et al. [2] produced coarse and fine lightweight aggregates from mixed waste of wastewater sludge and dredged material, fired within a temperature range from 1050 to 1200 deg C and crushed to smaller-sized aggregates for use in concrete. The aggregates were reported to exhibit high thermal insulation and fire resistance properties, with the 28-day compressive strength comparable to commercial lightweight aggregates.

With this as a basis, NewEarth (NE) developed a technology to transform the mixed waste of dredged material and spent copper slag into an environmentally safe material which can be used as value-added construction materials. The patented technology, also known as 'Crystallisation Technology' (Singapore patent number: 123864 [WO 2005/097368]) involves chemical, mechanical and vitrification techniques specially designed to process the mixed wastes. The process is described as follows:

- First the dredged material was air-dried in a holding tank for several weeks to achieve a consistent dryness in order to batch accurately by dry mass before grinded to particle sizes finer than 1mm to promote agglomeration for the ease of palletizing later on
- Dredged material and spent copper slag were then crushed and grinded to finer size, sieved to remove sand, sea shell, dried plants and others to obtain uniform and smooth mixture before water was added
- The mix was chemically treated by adding silica-based solution to it to stabilize the heavy metals
- The mix was further aged for at least 24 hours to enhance the stabilization effect and allow the development of dredged material bonding
- The mix was palletized to the desired sizes, then dried at a temperature of 100ºC overnight to remove water content
- Finally the mix was transferred to a muffle furnace and sintered at 1000ºC for about 600mins. During sintering at high temperature the silica-based additive will combine with the dredged material to form a ceramic surface which will encapsulate heavy metals from leaching out to its environment.

*Figure 2. Synthetic Aggregates*

The resulting synthetic aggregates produced are shown in Figure 2.

# 4. Properties of Synthetic Aggregates

## 4.1. Chemical Composition of Synthetic Aggregate

For the SEM-EDX test, the synthetic aggregate sample produced from a mix comprising 50% dredged material and 50% spent copper slag, was dried at 105ºC and sieved before elemental analysis. The normalized average element analysis results of the dried residue were obtained and listed in Table 1. The dominant elements are Al 7.38%, Si 22.7% Fe 17.7% and O 43.4%, which are common or ubiquitous elements found in dredged material and spent copper slag. After heat treatment is applied at 1000℃, majority of the elements will be oxidized to metal oxides, which is the reason for the high oxide, O content, 43.4% found in the sample. Metal oxides are very stable compounds which will not dissociate or be affected by pH of its environment.

*Table 1. SEM-EDX qualitative element analysis of Synthetic Aggregates*

| Element content, % | Element Analysis result (Qualitatively), based on average of 5 determinations |
|---|---|
| Sodium, Na | 1.34 |
| Magnesium, Mg | 0.41 |
| Aluminium, Al | 7.38 |
| Silicon, Si | 22.7 |
| Sulfur, S | 0.29 |

| Element content, % | Element Analysis result (Qualitatively), based on average of 5 determinations |
|---|---|
| Potassium, K | 1.80 |
| Calcium, Ca | 2.96 |
| Titanium, Ti | 0.47 |
| Manganese, Mn | 0.086 |
| Iron, Fe | 17.7 |
| Copper, Cu | 0.79 |
| Zinc, Zn | 0.69 |
| Oxygen, O | 43.4 |

XRD was also carried out on the above sample and treated at temperature of 1000 deg C. Based on the XRD pattern, the sample contains a mixture of 6 possible crystallization phases including quartz ($SiO_2$), Magnetite ($Fe_3O_4$), Haematite ($Fe_2O_3$), Halloysite -10A ($Al_2Si_2O_5(OH)_4 \cdot 2H_2O$), Andradite, syn ($Ca_3Fe_2(SiO_4)_3$), Hydrohematite ($Fe_2O_3 \cdot xH_2O$) and Iron, syn (Fe). Quartz is the main component which has the largest phase in the aggregate.

## 4.2. Physical Properties of Synthetic Aggregate

### 4.2.1. Water Absorption (WA)

The WA tests were conducted according to BS EN 1097-3 for the synthetic aggregates sintered at different temperatures. The WA performance is crucial especially when aggregates were to be used for concrete production. The amount of water absorbed by the aggregates will directly affect the concrete workability.

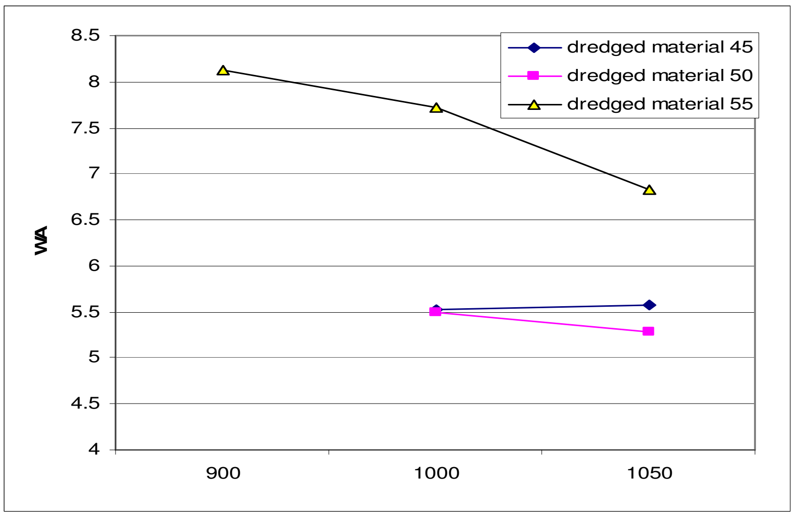



*Figure 3. Effect of temperature on WA of Synthetic Aggregates*

As shown in Figure 3, the WA data collected from our experiments ranged from 5% to 8%. Figure 3 also showed that generally as the sintering temperature increased, the WA rate of aggregates decreased correspondingly. When aggregates with dredged material 50% were tested at different temperatures it showed reduction in WA at 1000ºC and 1050ºC from 5.5% to 5.28%. This can be explained that at a higher sintering temperature as the dredged material and spend copper slag started to fuse, the micro-particles began to tightly bind together and developed a closed pore structure. I-J. Chiou et al. [3] explained that a glassy or ceramic texture will begin to form on the surface of the aggregates at high temperature, thus enhancing the WA performance of the aggregate. The exception was the aggregate with 45% dredged material. It was likely that at that proportion, insufficient bonding developed between the dredged material and copper slag resulting in pores forming between the micro-particles. Thus the WA increased from 5.52% to 5.58% even as the sintering temperature increased from 1000℃ to 1050℃.

### 4.2.2. Aggregate Impact Value

Aggregate Impact Value (AIV) tests were carried out according to BS 812: Part 112. AIV is a test of the aggregate strength. The AIV is expressed as a percentage of fines produced from the aggregate sample after subjecting it to impact from a standard plunger for 15 times.

As shown in Figure 4, an increase in dredged material content will reduce the AIV value. This is because dredged material helps to fuse and bind the mix together to enhance the strength of the resulting aggregate. When the dredged material content increased from 40% to 50% the AIV value decreased approximately 3% from 54% to 51%. Similarly a further increase in dredged material content to 65% will reduce the AIV value to approximately 48%.

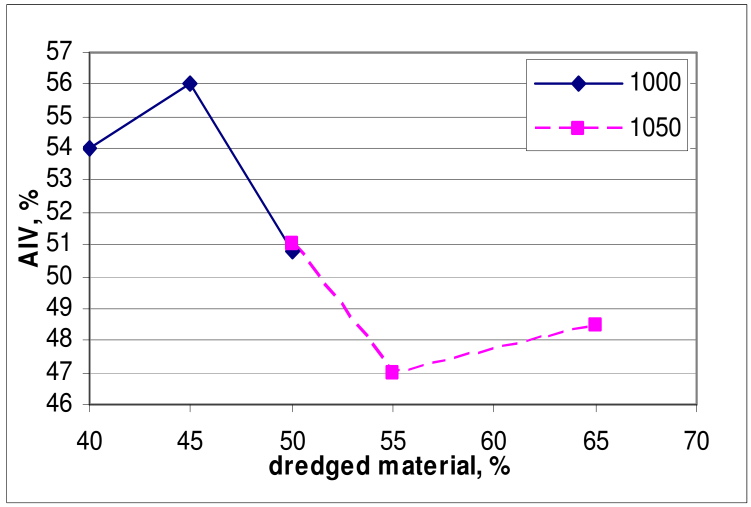



*Figure 4. AIV value at different dredged material %*

Interestingly, results also showed that an increase in sintering temperature significantly reduced the AIV. When sintered at 900ºC, the AIV value was 50% but when the sintering temperature increased to 1050ºC, the AIV value decreased to 47%. This can be explained that when the sintering temperature increased to 1050ºC, the SiO in the dredged material will fuse and hold the mix together to develop smaller pore size microstructure and form a ceramic outer layer which showed 'glassy' surface.

4.2.3. Loose Bulk Density

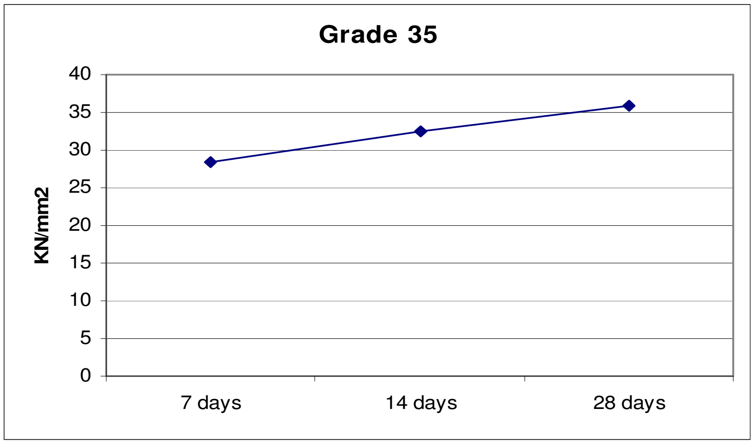
Loose bulk density of the synthetic aggregates was determined based on BS EN 1097-3. Results in Table 2 showed that the aggregates can be categorized as lightweight aggregates (below 1200kg/m3).

*Table 2. Loose Bulk Density of Synthetic Aggregates*

| Test No. | Loose bulk density, $kg/m^3$ |
|---|---|
| 1 | 1164 |
| 2 | 1127 |
| Average | 1145.5 |

## 5. Potential Applications of Synthetic Aggregates in Concrete

For concrete testing synthetic aggregates with 50% dredged material and 50% copper slag sintered at 1000ºC was selected and sufficient quantity was produced for the casting of concrete samples. Since the AIV values of the synthetic aggregates produced were relatively higher than conventional granite aggregates used for concrete (Max specified under BS 812: Part 112 was 45%), the project team comprising CSBC and NewEarth personnel decided to explore the use of these aggregates to replace granite aggregates for non-structural concrete applications for a start. This is despite the fact that there is no conclusive evidence of a direct correlation between the AIV and the compressive strength of concrete.




As the compressive strength of concrete is the most common performance parameter used by the engineers in designing buildings and other structures, the compressive strength tests of concrete produced using synthetic aggregates was conducted according to BS 1881: Part 116. Strength test results from cast concrete specimens may be used for quality control, acceptance of concrete, or for estimating the concrete strength of a structure for the purpose of scheduling construction operations.

*Figure 5. Compressive strengths of Grade 35 concrete*

The compressive strength is determined by crushing a concrete cylinder or cube specimen in a compression testing machine according to the requirements of BS 1881"Part 116.

For the trial tests, the compressive strengths of 6-inch concrete cube specimens cast with 100% replacement of granite aggregates with synthetic aggregates were evaluated.

The two most common grades of concrete used in the industry were produced- Grade 35 and Grade 40. All the industrial standard practice in concrete mixing remains unchanged. Workability of the concrete was not compromised because of the low WA characteristic of the aggregates. All the concrete cubes were water-cured under standard laboratory conditions until their specified ages at 7, 14 or 28 days. Results of the concrete compressive strengths are as shown in Figures 5 & figure 6. The 28-day strengths of both grades of concrete were satisfactory.

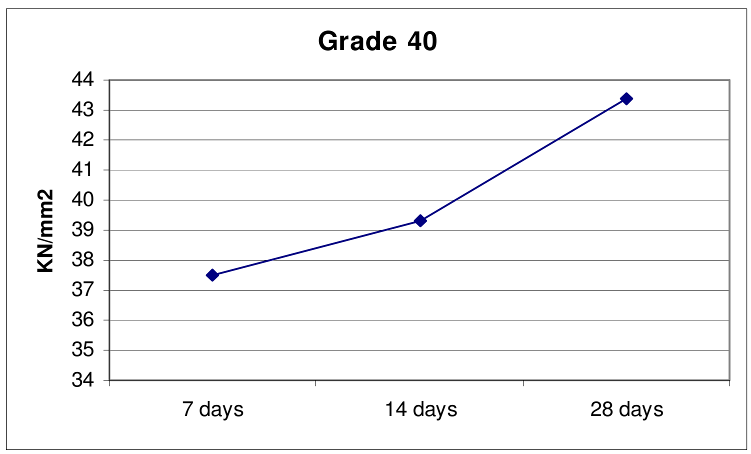



*Figure 6. Compressive strengths of Grade 40 concrete*

Due to certain constraints in this project, an actual field test could not be carried out using the synthetic aggregate mix. For the next phase of the study field concrete produced using the optimised synthetic aggregate mix would be subjected to various tests according to the existing building codes and regulations.

## 1. Environmental Impact of Synthetic Aggregates

To assess the environment impact due to leaching of heavy metals from the synthetic aggregates, the Toxicity Characteristic Leaching Procedure (TCLP) test was carried out according to the US EPA 1311 standard. Results are as shown in Table 3.

*Table 3. 3rd Party Verification Test on Leachability of Heavy Metals*

| Element, mg/L | Synthetic Aggregate | Maximum allowable Concentration |
|---|---|---|
| Arsenic, As | 0.15 | 5 |
| Barium, Ba | 0.37 | 100 |
| Cadmium, Cd | <0.0012 | 1 |
| Chromium, Cr | 0.020 | 5 |
| Copper, Cu | 1.13 | 100 |
| Cyanide, CN | <0.06 | 10 |
| Fluorine, F | 3.26 | 150 |
| Iron, Fe | 1.02 | 100 |
| Lead, Pb | 0.099 | 5 |
| Manganese, Mn | 0.028 | 50 |
| Mercury, Hg | <0.0001 | 0.2 |
| Phenolic compounds | <0.15 | 0.2 |
| Selenium, Se | <0.045 | 1 |
| Silver, Ag | <0.0015 | 5 |
| Zinc, Zn | 0.35 | 100 |
| Nickel, Ni | <0.0045 | 5 |

It was observed that the highest concentration levels recorded were Cu (1.13mg/L), F (3.26mg/L) and Fe (1.02mg/L). However, the concentration levels for the leached heavy metals were very low or negligible. This means that the environmental impact of the synthetic aggregates is minimal and affirmed NewEarth's patented 'Crystallization Technology' is effective in encapsulating the heavy metals from the dredged material and spent copper slag from leaching out. The use of high temperatures to convert the structure of the industrial wastes into a ceramic matrix is an added advantage. The resulting structure is very stable and would not pose any environmental problems in the long term. The ceramic aggregates are therefore safe for reutilization and are suitable to be used for value-added building and construction applications.

## 2. Conclusion

This study showed that the production of synthetic aggregates using industrial wastes such as dredged materials and spent copper slag for building and construction purposes is not only feasible but sustainable. The aggregates had a bulk density of less than 1200kg/m$^3$, therefore it is classified as lightweight aggregates. Although the AIV is higher than conventional granite aggregates, the aggregates are still suitable to be used for non-structural concrete. Workability of the concrete was not compromised because of the low WA characteristic of the aggregates. Achieving the designed strengths of Grade 35 or 40 concrete was not an issue. TCLP test also showed that the synthetic aggregates did not pose any hazardous impact to the environment.

The success of the project offers an alternative to landfill and aids in prolonging the lifespan of Singapore's only offshore landfill site at Pulau Semakau. Most importantly the feasibility of using synthetic aggregates also reduces Singapore's reliance on imported construction materials. By replacing natural aggregates with synthetic aggregates, valuable natural resources can thus be freed up and utilized for higher- value applications.

## 3. References

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