MyConcrete

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The Bulletin of the American Concrete Institute – Malaysia Chapter

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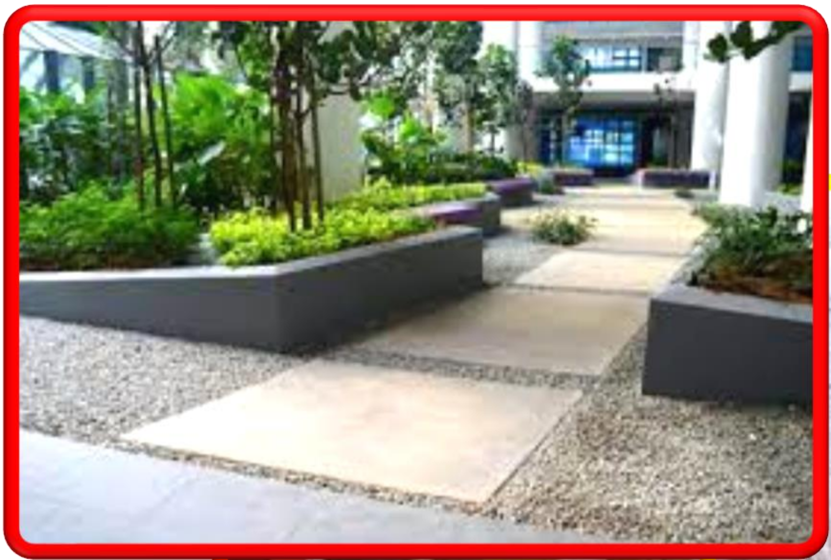

MyConcrete:

The Bulletin of the American Concrete Institute – Malaysia Chapter

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CONTENT

EDITORIAL NOTE

ACI – Malaysia Chapter publishes MyConcrete as its official monthly bulletin. It publishes valuable cutting-edge research and case studies on concrete construction. We are presenting the seventh issue of volume twelve of the bulletin.

This issue contains an industry article, a technical report, and a case study on concrete technology. The first article discusses the optimum size of industrial concrete floor slab casted as a single panel without any cracks and defects. It discusses the major challenges the construction industry is facing to construct a crack-free slab with some improvement recommendation for crack free slab on ground. On the other hand, the technical report focuses on the use of wastes materials as alternative fuel in cement manufacturing. The report provides a brief overview on potential application of waste tyres, municipal solid waste (MSW), and sewage sludge (SS) as alternative fuel in cement production. Finally, a case study on producing concrete formwork through additive manufacturing is presented. The work reported a cutting-edge restoration process of a historic building in Germany.

The editorial team would like to express our gratitude to the individuals' contributing articles for this issue of MyConcrete bulletin. We believe all the article provides valuable insights for the concrete practitioners. The editorial team would like to invite concrete technologist and engineers to contribute articles for the upcoming issues of MyConcrete bulletin.

The team would like to thank Master Materials Manufacturing Sdn. Bhd. for sponsoring this issue as a premium sponsor. We also would like to thank NCL Chemical & Equipment Sdn. Bhd. And Impianti Sdn. Bhd. as our loyal sponsor for this issue. The sponsorship for upcoming issues is open for the concrete companies. The team anticipates in getting more sponsorship for the upcoming issues.

Thank you very much. Happy reading.

Dr. A. B. M. Amrul Kaish
Editor, MyConcrete Bulletin

INTRODUCTION TO ACI MALAYSIA CHAPTER

American Concrete Institute - Malaysia Chapter (ACI-Malaysia) is a non-profit technical and educational society representing ACI Global in Malaysia, which is one of the world's leading authorities on concrete technology. Our members are not confined to just engineers; in fact, our invitation is extended to educators, architects, consultants, corporate, contractors, suppliers, and leading experts in concrete related field. The purpose of this Chapter is to further the chartered objectives for which the ACI was organized; to further education and technical practice, scientific investigation, and research by organizing the efforts of its members for a non-profit, public service in gathering, correlating, and disseminating information for the improvement of the design, construction, manufacture, use and maintenance of concrete products and structures. This Chapter is accordingly organized and shall be operated exclusively for educational and scientific purposes.

Objectives of ACI-Malaysia are:

- ACI is a non-profitable technical and educational society formed with the primary intention of providing more in-depth knowledge and information pertaining to the best possible usage of concrete.

- To be a leader and to be recognized as one of Malaysia's top societies specializing in the field of concrete technology by maintaining a high standard of professional and technical ability supported by committee members comprising of educators, professionals and experts.

- Willingness of each individual member/organization to continually share, train and impart his or her experience and knowledge acquired to the benefit of the public at large.

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Important Notes:

i) ACI Malaysia is only a platform for our members to advertise for interns.

ii) All application to be made direct to companies and would be subject to their terms and conditions.

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Topic: Riding Through The Storm

- 'What can be done to go through this pandemic period as a construction leader'

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Panelists: Mr. Eric Soong
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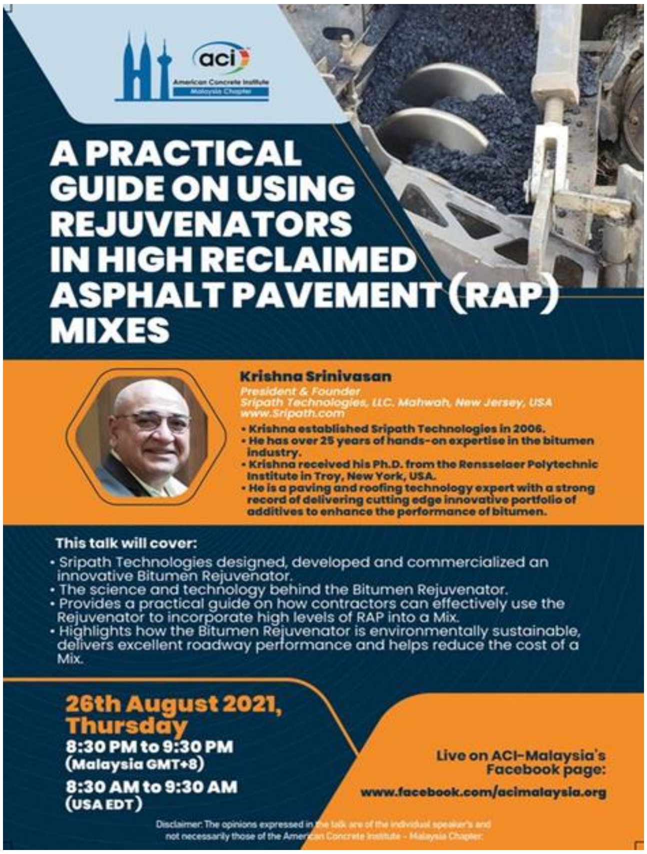

ARTICLE

How Big A Concrete Floor Slab Can Be Casted Without Cracks?

Written by: Dr. Zack Lim

This article is to discuss what is the optimum size a concrete floor slab can be casted in a single panel without any cracks and defects especially in the industrial floor sector which demand for high quality floor. Even though the technology behind the construction of concrete slab has improved over the years, besides expecting a floor to be build flat and level, one of the major challenges facing the construction industry is how to built a 'crack-free slab. Concrete being a vagarious material tends to crack due to various reasons but mainly caused by drying shrinkage, thermal movement and restraints. Therefore, concrete floor cracking may be caused by a single factor but also combination of two or more factors. As such designers and builders can only endeavour to mitigate, minimize, or control cracks but almost impossible to guarantee constructing a large concrete slab with no cracks.

1.0 Why big slabs are preferred?

If slabs are casted in smaller panels and without restraints, cracks can easily be avoided but to construct a large size panel, for example 1,000m^2 in a single pour successfully without any form of cracks and defects will be a challenge. Large slabs are preferred as it speed up the job, contain less construction joints and contraction joints which are potential weakness on the slab if not properly constructed as shown in Figure 1. The other advantage of minimum joints is to reduce curling of slab at edges as shown in Figure 2. Such curling defects will disrupt smooth operation of lift-trucks and spalling at joints resulting in continuously costly repair.

Figure 1. Damage at joint.

Figure 2. Curling at slab edge.

2.0 Construction of concrete floor slab (slab-on-grade)

Concrete has high compressive strength but low tensile strength and tensile strength of the concrete is only about 10% of the compressive strength, therefore concrete will crack when the tensile stress within exceeds the tensile strength of the concrete. Hence, one way to mitigate cracks is to lower the tensile stress in concrete and to increase the tensile strength of the concrete. When cracks occurred, blame goes to poor workmanship, poor quality of concrete supplied or improper design. In actual facts, any cracks resulted could be man-made or caused by factors to be discussed as follows.

Common factors which may contribute to cracking in floor slabs:

2.1 Ground settlement

Subgrade is the original ground and it is best to carry out a soil investigation to study the soil bearing capacity to support the intended design load. Any filling materials selected for filling shall be suitable for easy filling and well compaction. A well-compacted sub-base will facilitate loaded vehicles to roam the construction site freely without rutting the surface and also a simple proof rolling method to ensure the subgrade and sub-base are well compacted to prevent settlement cracks.

2.2 Contraction joints

As thicker slab is stiffer and will tend to produce less cracks compared to a thinner one unless the later is specially designed. Likewise, a thinner slab will also tend to curl more than a thicker slab of similar mix design and working condition. Therefore, to avoid random cracking, contraction joints are created on weak planes on the slab surface at locations where high stresses accumulate and prone to cracks. In fact, contraction joints are simply pre-determined man-made straight line cracks created to release stresses on the floor surface to induce cracks when the slab commence to shrink, being straight line man-made cracks, nobody complains. If contraction joints are not provided to dissipate the stresses, random cracks will be unavoidable. The contraction joints are carried out using mechanical diamond saw machines on the next day or the same day if a green blade is available. The depth of cut is normally one-fourth of the slab thickness and the saw-cutting is carried out immediately when the concrete gained sufficient hardnesss, normally between 8 to 12 hr after the floor is finished. To mitigate random cracks, contraction joint spacings of maximum 36 times the slab thickness, up to a maximum of 5.5meter have produced acceptable results (ACI 302.1R-04). If a slab is 150mm thick, the contraction joints need to be spaced at every 5.4meter.

On contrary, wider contraction joints spacing of up to 16m x 16m have been successfully carried out reinforced with 20kg/m3 of steel fibres without any forms of cracks.

2.3 Type of reinforcement and positioning

To select welded mesh or steel bars as reinforcement for crack control is one task but placing and positioning the reinforcement at right location is the challenge. The purpose of reinforcement is to provide additional strength where needed and if cracks happened, it supposed to keep the cracks tight and preventing it from opening and becoming wider. If the location of reinforcement is wrongly placed, for example, placed lower than mid section of slab, it will defeat it purpose and may not performed. It is best to position about 30mm from the surface for crack control. To overcome such difficulty to position the reinforcement right, steel fibres or synthetic fibres are used as a replacement for better crack control. Generally, fibres will provide better crack control as they are 3-dimensionally distributed within the concrete slab to absorb any tensile stresses which occur at early stage when the young concrete is yet to achieve the tensile strength to resist cracks. When early micro-cracks developed, the fibre strand will intersect and blocked the micro-cracks from developing into macro-cracks as the concrete shrinks.

2.4 Concrete mix design

Concrete mix design is of utmost important not only to produce high strength concrete but to achieve good workability, cohesiveness, durability and minimum shrinkage to mitigate cracks. The main cause of cracks resulted from volumetric changes of concrete as the water evaporates gradually resulting in shrinkages.

As a rule of thumb, every 6m of concrete slab, can shrink as much as 3mm, as such it is advisable to use lowest permissible water/cement ratio for the concrete mix design without affecting the workability as water being the single greatest factor affecting shrinkage. Research confirmed that 1% increase in water will increase shrinkage by about 2%. When the concrete is still in the plastic phase, the concrete surface dries and shrinks so rapidly that tensile strain exceed the strain capacity of the young concrete which will results in plastic shrinkage cracks. Designing a concrete mix right with minimum shrinkage of less than 3% will certainly reduce drying shrinkage cracks and with high early strength will avoid early thermal cracks. Another important consideration is the type of cement used as Ordinary Portland Cement (OPC) will achieve initial set faster with early strength compared to supplementary cementitious materials like pulverised fly ash addition.

Therefore, one way to design concrete using minimum water without affecting the workability of the concrete by selecting and packing graded fine aggregate, coarse aggregate with selective superplasticizer in the mix. For construction of floor slabs, the recommended cement content using OPC shall be below 400kg/m3 to avoid curling of slab.

2.5 Poor detailing.

Design error and poor detailing will expose the slab to greater stresses than it can handle, resulting in cracking. For example, cracks propagated from corners of columns (as shown in Fig. 3) was caused by diagonal re-bars being omitted (shown in Figure 4). Such re-entrance corner cracks happen in all floor openings and columns where stress concentration are high.

Figure 2. Diagonal re-bars.

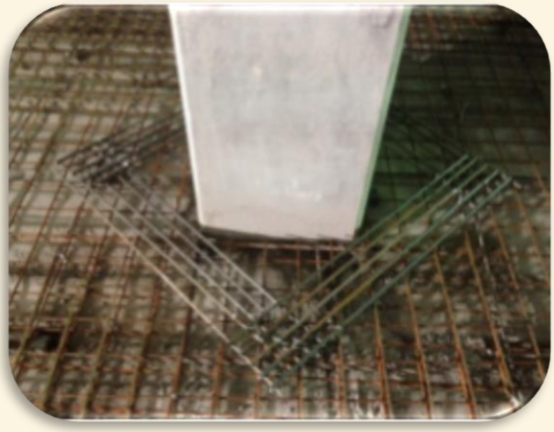

Figure 4. Re-entrance crack.

2.6 Slab size and aspect ratio of width/length

Slabs are generally casted in narrow strip, wide bays or large pour. The recommended aspect ratio of width/length is preferably 1:1 and not to exceed 1:1.5 as mentioned in "Guide for Concrete Floor and Slab Construction", ACI 302.1R80. Any floor panels with excessive width-to-length ratios as mentioned will tend to crack to release stresses at the mid-panel surface or at locations with excessive stresses. However, this recommended width-to-length ratio could only be extended to 1:2 or more subjected to better understanding of crack control, adding special admixture to reduce stress in concrete like shrinkage compensating admixture.

Conservatively, recommendation of each panel size to be casted as follows.
For slab on grade: External slab, each panel 4.5m x 4.5m with contraction joints.
Internal slab, each panel 6.0m x 6.0m with contraction joints.
For slab on piles: each cast 20m x 20m
For elevated slabs: each cast 20m x 20m

There is no guarantee that no cracking will be observed based on the above said recommendation as concrete cracks can be considered normal, even though in practice, there were claims that slabs which were 2 to 3 times larger than above-mentioned have been done successfully.

2.7 Joints - Isolation joints, contraction joints, etc

For slab-on grade, casting of slabs can be carried out in large pour within a day but contraction joints (e.g. 6m x 6m interval) need to be performed to induce cracks within the slab to avoid random cracking. When the slab gradually shrinks and contracts, the cutted joints will slowly open up.
As for construction joints for slab-on-grade, dowel bars need to be installed to cater for load transfer.
As for suspended slabs, all construction joints need the reinforcement bars to be continuous.
As for slab on piles, movements joints or expansion joints need to be designed at probably every 30 to 50m to facilitate expansion and contraction due to panel shrinkage and temperature change.

2.8 Restraints of slab

For a slab on grade floor built on a well-compacted ground with reasonable flatness and levelness will allow the slab to slide freely with the sub-base with no surface restraints. As for suspended slabs, restraints will mainly be from the columns, beams, reinforced walls and openings.

For slab-on-grade there are several forms of restraint that prevent the concrete from shrinking freely in the form of internal or external forces as follows.

i. Internal restraint
Normally for thicker slab (normally about 1 m thick) where thermal cracks can occur due to temperature difference between the surface zone and the internal core of the concrete. The surface of an element will cool faster (contraction) than the hot core (expansion), thus resulting in early thermal cracks and delayed ettringite formation if the temperature difference between the core and the surface exceeds 20◦C.

ii. Surface restraint
The resistance to allow the slab to slide freely onto the existing sub-base can be achieved by better flatness control on the sub-base surface. To further reduce the coefficient of friction between the slab and the sub-base, placing a slip membrane using polyethylene sheets with thickness of 0.25 mm is highly recommended besides acting as a moisture barrier.

iii. End restraint
Cracks often occurs when floor slab is not permitted to move freely especially when the floor reinforcement is tied to walls, beams and columns. For slab-on-grade, it is best to isolate the floor slab from such fixed structures to release any stresses. Likewise, all four ends of a floor panel should be debonded wherever possible from the ground beams or walls.

iv. Edge restraint
When casting strip pour (long and narrow slab) try to avoid casting the entire infill slab (panel between two completed adjacent slab) at one go if it is too long (>30 meters), alternatively contraction joints if permitted should be allowed to control any transverse cracks.

2.9 Curing
Curing is the process of controlling the rate and extent of moisture loss from concrete by trapping the water needed for the chemical reaction during cement hydration. Curing allows the concrete to achieve its potential strength and durability. Late curing or no curing is often cited as a major factor that caused surface defects like craze cracks and loss of concrete strength as much as 30%. As such, early and proper curing is essential to achieve the concrete strength needed and to improve abrasion resistance. Finally, to reduce drying shrinkage, proper curing should be carried out for at least 7 days as 80% of ultimate shrinkage is caused by inadequate or no curing.

2.10 Early thermal cracking
During the hydration process when the cement reacts with water, the chemical reaction produces heat. In hot countries, compounded with the direct heat from strong sunlight onto the slab surface, it will cause the temperature of the slab to rise, resulting in thermal volume change which expand the slab. Subsequently, during the night when the concrete cools, it contracts and since the tensile strength of the concrete being relatively low may lead to cracking.

2.11 Shrinkage control

Ordinary Portland Cement concrete shrinks as it dries, this shrinkage if restrained is conducive to cracking. Therefore, to eliminate drying shrinkage cracks, a shrinkage compensating cement is added to make the concrete expand vey slightly (about 0.0045%). This shrinkage compensating cement is designed to provide dimensional stability during the concrete curing period when the young concrete with low tensile strength is susceptible to crack when the tensile stress exceeds it. This shrinkage compensating cement will expand very slightly when added into concrete which compensate the drying shrinkage as it begins to dry. As the concrete sets, it bonds to the steel reinforcement and while the concrete is curing and gaining strength, the expansive reactions provide a slight controlled elongation to the concrete. The bond to the reinforcement steel causes it to be stretched slightly and places the steel in tension. Whilst the reinforcement steel is in tension, the concrete is thus put in slight compression which is favourable. With shrinkage compensating concrete, not only it will minimize cracks but the joint spacing can also be doubled.

3.0 Conclusion

There is no arbitrary limit on the size of the slab to be poured in a single day if reasonable crack width is allowed and acceptable but to build a large slab without any form of cracking and defects is the biggest challenge.
The maximum size of pour shall be determined by practical considerations such as the followings:

1. Can the concrete supplier provide continuous supply of concrete without any interruption to avoid defects like cold-joints?

2. Does the contractor have sufficient well-trained manpower with good construction practices and technical know-how to execute such large slab?

3. Are there sufficient, "state of art" machinery and equipment to fulfil the objective and meet the specified floor requirement?

In conclusion, to construct a large floor slab without or minimum cracking, a composite concrete system is recommended by adding shrinkage compensating compound, lower water/cement ratio, heavier reinforcement and follow the best construction practices.

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TECHNICAL REPORT

The Potential Of Wastes As Alternative Fuel In Cement Manufacturing

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Abstract

The annual production of cement is enormous, as concrete is one of the most widely used construction material. Cement manufacturing industry has been regarded as one of the industries that heavily consumes energy. Thermal energy has been accounted for occupying a large portion to the cement production cost, which is approximately 20-25%. In addition, the environment impact due to the use of fossil fuels as a result of mining and burning is not favourable. Therefore, partially substituting traditional fossil fuels with alternative fuels for cement manufacturing is drawing attention. Fossil fuels that have been used are, but not limited to, waste tyres, municipal solid waste, and sewage sludge. Each alternative fuel has a distinct calorific value, which is dependent on their source and treatment process. The availability of alternative fuel is also different from one place to another. Therefore, in-depth evaluation is required for using alternative fuels so that it would not incur environmental issue, increase the cost or degrade the quality of cement clinker.

1. Introduction

Concrete is the most widely used construction materials globally is commonly produced by mixing of cement with aggregates and water. Figure 1 shows the world cement production by regions and major countries in the year of 2018. In 2019, the worldwide cement production is reported to be at 4 billion tons, which is about 50% increment from the year 2005 [1].

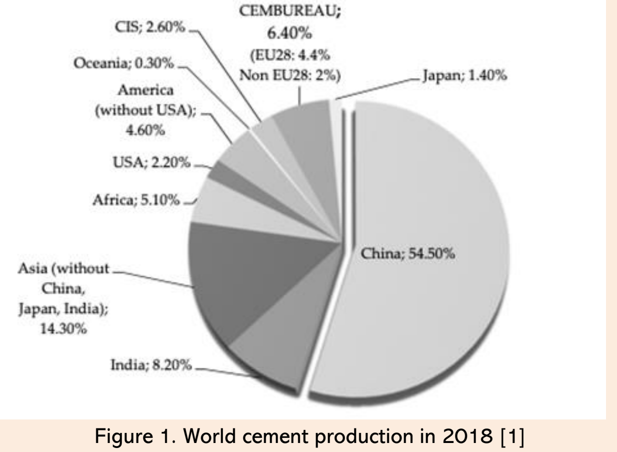

Figure 1. World cement production in 2018 [1]

Cement manufacturing industry is regarded as one of the industries that consume huge amount of energy. About 20-25 % of the production cost is accounted for supplying the thermal energy [2], where the thermal energy is mainly obtained by burning of traditional fossil fuels such as coal, petcoke, oil, and natural gas [3]. Besides that, cement manufacturing has some environmental impact, attributed to the emissions of CO_2, NO_x, and SO_2. Various efforts have been made to reduce the energy consumption and environmental impact in cement manufacturing, including the usage of waste as alternative fuel.

Utilization of alternative fuels in the cement manufacturing process has drawn significant attention globally in the past few decades. This is due to its effectiveness in meeting the thermal energy requirement. In addition, adopting alternative fuels can help in reducing the dependency on non-renewable fossil fuels, as well as the negative impacts caused by the mining process. Besides that, replacing fossil fuels with alternative fuel from wastes can lower the greenhouse gas emission and environmental impact as the wastes would otherwise be incinerated or disposed. Furthermore, utilization of waste as alternative fuels can be considered as a rapid waste treatment method, where large quantities of wastes are being burnt off in a relatively short span of time [4].

2. Alternative fuels

Some of the wastes used as alternative fuels that have been adopted in the cement manufacturing industry are introduced here, including but not limited to waste tyres, municipal solid waste (MSW), and sewage sludge (SS).

2.1. Waste tyres

Waste tyres that originate from the automobile industry is generally disposed to the landfill. However, in the mid 80s, the waste tyres have become a popular alternative fuel in the cement manufacturing, attributed to the spike in the fossil fuel price. In addition, the high carbon content and heating value of waste tyres, as well as its low moisture content made it a potential alternative fuel. Different form of waste tyres have been used, including whole tyres, shredded tyres and fine grained tyres [3]. Figure 2 shows the waste tyres that have been used as alternative fuel in cement manufacturing.

Figure 2: Waste tyres and tyre chips [5]

According to Pipilikaki, Katsioti [6], the usage of waste tyres as alternative fuel is restricted to a maximum replacement of 30 % to avoid adversely altering the produced cement quality due to presence of high quantities of zinc in waste tyres. On the hand, Nakomcic-Smaragdakis, Cepic [7] investigated that the emission level of NOX and SO2 when 0-15 % of waste tyres were used. The emission was found inconsistent, where in some cases, the emission was reported to be slightly decreased while there are also reports that the emission was found increased.

2.2 Municipal solid waste (MSW)

Incineration of MSW is a popular management option instead of disposal to landfill, particularly where recycling or reuse is not possible. Incineration of MSW not only help to reduce the volume of the waste, energy and valuable materials (metals) can be recovered as well [8]. The co-processing of MSW as alternative fuel for cement manufacturing is another potential treatment option. In addition, the landfill tipping fees can be reduced, as well as decreasing the generation and supply of fossil fuel. Nonetheless, unsorted MSW is not directly burnt due to its heterogeneous nature [9]. Figure 3 shows the unsorted and sorted MSW. The unsorted MSW will be first sorted and then converted into refuse-derived fuel (RDF), as shown in Figure 3 and Figure 4.

Figure 3: Sorting of MSW [10]

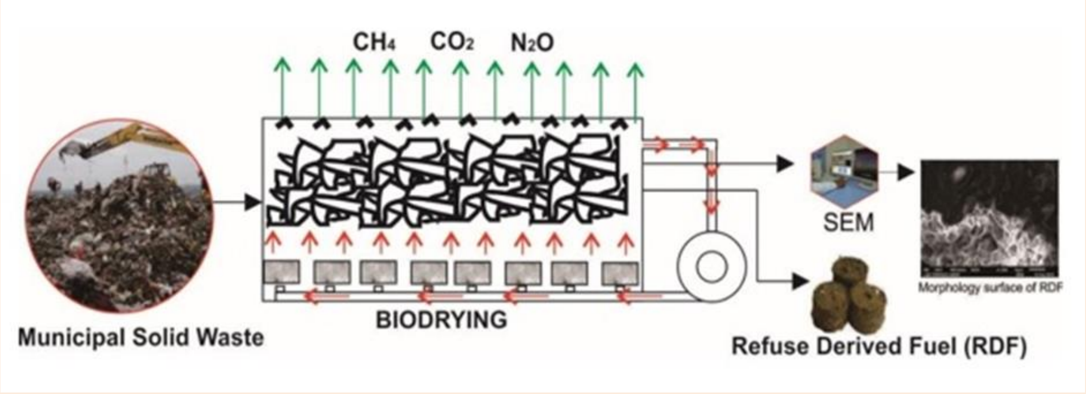

Figure 4: Conversion of MSW into RDF [11]

Hemidat, Saidan [12] stated that the calorific value of MSW was increased by about 58% when the moisture content of the MSW is reduced via drying process. Furthermore, addition of 15 % of MSW as alternative fuel did not result in any degradation on cement clinker quality and increment in the flue gas emission values. Such substitution was reported to be able to save up to 23,328 ton of petcoke per year, 16,330 tons of CO2 emission to the atmosphere, and a net saving of 2,798,902 USD annually. Similar substitution level of MSW to the fuel was reported by Sakri, Aouabed [13]. Based on the life cycle approach, Çankaya [14] reported that the climate change could be reduced by 12-27 % when 15-30 % of the fossil fuel was substituted by MSW.

2.3. Sewage sludge (SS)

SS is a by-product that is generated during the wastewater treatment process. Disposal of SS has become more restricted over the years [15]. The water content of SS is high, which is unfavourable to be used as alternative fuels. Thus, the SS is usually dried before used as an alternative fuel. Figure 5 shows the fuel that is derived from the sewage sludge. In 2006, around 40,000 tons and 54,964 tons of dried sewage sludge was used as alternative fuel in German and Switzerland, respectively [16].

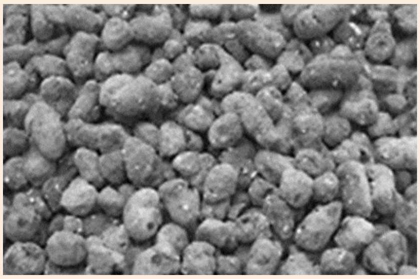

Figure 5: Sludge-derived fuel [17]

The feeding rate of SS is limited to be less than 5 % of the clinker production capacity [18]. Conesa, Gálvez [19] reported that there was no correlation with the usage rate of SS with the heavy metal emission, while Cartmell, Gostelow [20] found contradictory outcomes. On the other hand, based on the life cycle approach, the substitution of 15 % of SS with the fossil fuels in the cement industry increased the climate change by 0.5% [14].

3. Calorific value

The energy potential of a waste as alternative fuel can be determined by measuring its calorific value. The calorific value (heating value) of a fuel is the amount of heat that can be generated per kg (solid or liquid) or per m3 (gas) of the fuel.

According to Nakomcic-Smaragdakis, Cepic [7], an average of 3300 MJ of thermal enery is required to produce one ton of cement, which corresponds to 132 kg of coal that has a calorific value of 25 MJ/kg. The higher the calorific value, the lesser the amount of the fuel is needed to supply the required thermal energy. Table 1 tabulates the calorific value of the fuels that have been used in the cement manufacturing. The calorific value of a similar type of fuel may vary from one to another, as this is affected by the source and treatment process.

Table 1: Calorific value of fuel

Fuel	Calorific value (MJ/kg)	Reference
Fossil fuel		
Coal	22.70 – 28.81	Wojtacha-Rychter, Kucharski [1]; Pamungkas and Hadi [21]
Petcoke	31.9	Nakomcic-Smaragdakis, Cepic [7]
Alternative fuel		
MSW	8.63 – 15.58	Ungureanu, Jozsef [4]; Nordi, Palacios-Bereche [22]; Hemidat, Saidan [12]; Wojtacha-Rychter, Kucharski [1]
SS	9 – 29	Fytili and Zabaniotou [23]
Plastic	29 – 40	Rahman, Rasul [3]; Wojtacha-Rychter, Kucharski [1]
Waste tyres	34.74 – 36.77	Karell and Blumenthal [24]; Pipilikaki, Katsioti [6]; Nakomcic-Smaragdakis, Cepic [7]
SPL	8 – 25.2	Mikša, Homšak [25]
MBM	14.47	Senneca [26]

4. Conclusion

Alternative fuels can play an important role to reduce the energy and environmental impact associated with the use of traditional fossil fuels in cement manufacturing. Several alternative fuels that have been used in the cement manufacturing globally is briefly discussed, which includes waste tyres, municipal solid waste, and sewage sludge. Most of the investigation point towards the feasibility of using alternative fuels in cement manufacturing. Alternative fuels from different wastes, or even the same type of alternative fuel but from different sources, may exhibit significant difference in their combustion effect. Therefore, selection of alternative fuels requires thorough investigation consideration so that it would not incur additional cost, create environmental issues and/or degrade the quality of cement clinker.

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CASE STUDY

Reprint from: CI Magazine

Formwork Produced Using Additive Manufacturing

A twenty-first-century process is applied to a historic restoration project

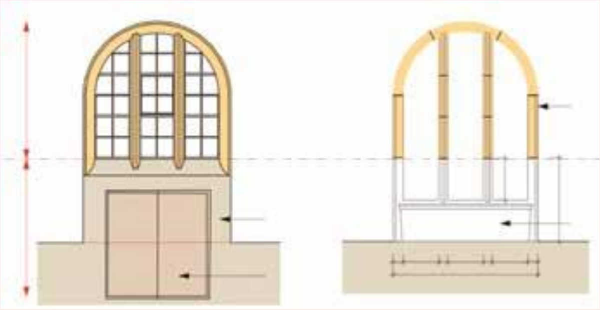
Building restorations can create challenges. Geiger Group found itself facing such challenges as it approached the conversion of the Allgäuer Brauhaus, a historic brewery in Kempten, Bavaria, Germany, into an office and events space. Geiger Group, founded in 1923 and based in Oberstdof, specializes in property development, construction, and civil engineering. The brewery project created a challenge: the need to replace five large stone window frames while retaining the original aesthetic of the historic façade.

The traditional method for such a project would be to reconstruct the frames using stone masonry. While such construction can produce great results, it is time-intensive, requires highly skilled workers, and is costly. Another, more economical option would be to reconstruct the frames using concrete elements produced using resin-coated formwork milled from blocks of expanded polystyrene foam. However, the depth of the frames on this project meant that it would not be possible to mill the formwork from a single piece of foam. Therefore, several pieces would have to be milled, resulting in increased costs and time to completion.

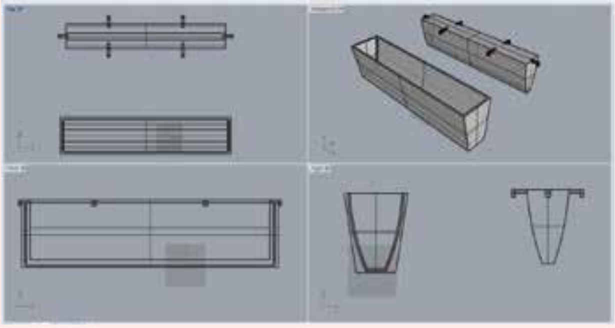
Because the project was on a tight schedule, Geiger reached out to BigRep GmbH to explore a third option. BigRep is a producer of industrial large-format three_x0002_dimensional (3-D) printers and printing materials. BigRep's team of experts works to create custom industrial application solutions using cutting-edge production methods and processes such as additive manufacturing. As a key player in the research sphere, BigRep's research and consultancy team is leading the quest to discover the future of industrial manufacturing and products.

After discussing the possibilities, BigRep and Geiger agreed to collaborate on the window frames, and they produced concrete frame elements through the following process:

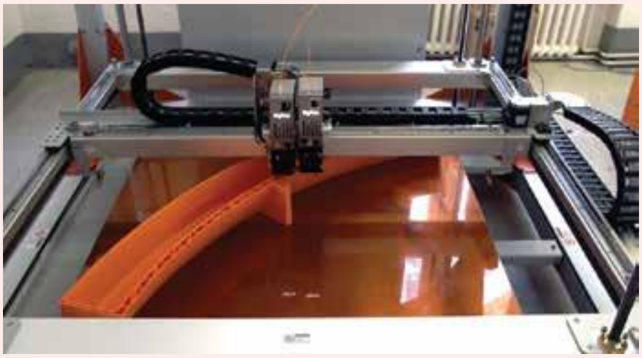
- Geiger provided BigRep with computer-aided design (CAD) files specifying the geometry of the window frames;
- BigRep worked from these files to generate a digital pattern (G-code) for the formwork components using 3-D printing slicing software;
- BigRep printed formwork for the brewery on a BigRep ONE printer, taking dvantage of its 1 m^3 (1.3 yd^3) build volume and using BigRep's biodegradable polylactic acid (PLA) printer filament material;



The restoration of the historic brewery required replacement of large elements of five window frames



3-D models of formwork elements were generated for the custom window frame elements



A formwork element takes shape within a 3-D printer

Concrete elements were assembled and installed at the project site

The window frames near completion. After the joints were mortared, the frames were painted to complete the façade restoration

- The forms were shipped to a concrete producer to cast window frame elements; and
- The frame elements were shipped to the construction site,

where the various sections were assembled and installed.

Although the client provided CAD files for this project, it should be noted that BigRep can alternatively produce CAD files and formwork using 3-D scans of template pieces. Geiger estimates that the window frame elements produced using BigRep's process cost 50% less than they would have from a stonemason, with a 45% shorter production time than if Geiger had opted for the resin_x0002_coated foam formwork option. Geiger was also able to

considerably reduce staff resources needed for the project. Combined with a high-quality finish, the process was the perfect solution for Geiger.

— Geiger Unternehmensgruppe, www.geigergruppe.de

— BigRep, www.bigrep.com

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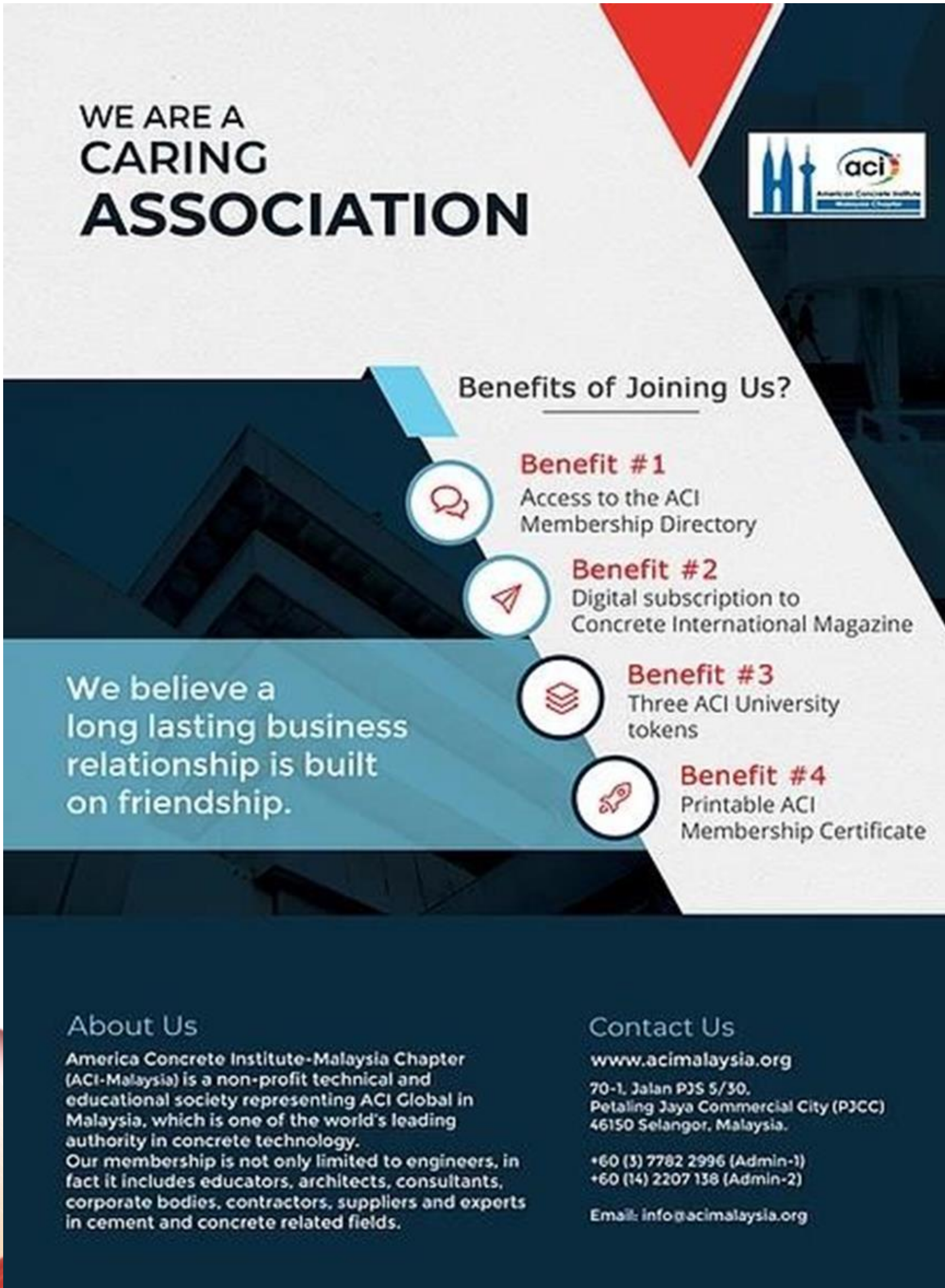
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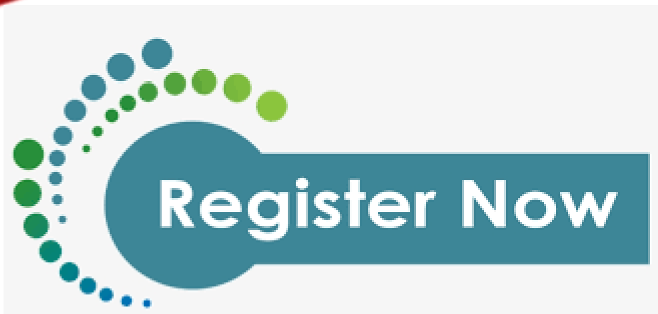

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