

1 **Mechanical and Durability Performance of Marine Sand**
2 **and Seawater Concrete Incorporating Silicomanganese Slag**
3 **as Coarse Aggregate**

4 Matthew Zhi Yeon Ting, Kwong Soon Wong, Muhammad Ekhlaur Rahman,
5 Selowara Joo Meheron

6 **Matthew Zhi Yeon Ting**

7 Department of Civil and Construction Engineering, Faculty of Engineering and Science,
8 Curtin University, Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia

9 Email: matthew.ting@postgrad.curtin.edu.my

10
11 **Kwong Soon Wong (Corresponding author)**

12 Department of Civil and Construction Engineering, Faculty of Engineering and Science,
13 Curtin University, Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia

14 E-mail: wongkwongsoon@curtin.edu.my

15 Tel: +6085 443939

16 Fax: +6085 443837

17
18 **Muhammad Ekhlaur Rahman**

19 Department of Civil and Construction Engineering, Faculty of Engineering and Science,
20 Curtin University, Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia

21 E-mail: merahman@curtin.edu.my

22
23 **Meheron Selowara Joo**

24 Department of Civil and Construction Engineering, Faculty of Engineering and Science,
25 Curtin University, Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia

26 E-mail: meheron.sj@curtin.edu.my

1 **Abstract**

2 This experimental investigation has validated the feasibility of utilizing
3 silicomanganese (SiMn) slag, marine sand and seawater in concrete production.
4 Compressive and splitting tensile strengths of concrete were evaluated. Assessment was
5 also performed on concrete durability which included water absorption, sorptivity,
6 chloride penetration and sulphate resistance. SiMn slag was found to reduce concrete
7 compressive and tensile strengths by 9.2% and 17.5% respectively. Nevertheless, the
8 concrete exhibited comparable durability to conventional concrete at 90-day age,
9 though it showed reduced value at 28-day age. The research also illustrated that marine
10 sand improved concrete durability by at least 42.3% and 11.5% in aspect of sorptivity
11 and chloride penetration respectively, while seawater showed little effect. More durable
12 concrete can be produced by utilizing SiMn slag, marine sand and seawater for potential
13 industrial application.

14 **Keywords:** Silicomanganese (SiMn) slag, Marine sand, Seawater, Compressive
15 strength, Splitting tensile strength, Concrete permeability

16

1 **1. Introduction**

2 The demand of concrete has increased rapidly due to robust growth in construction
3 industry. More recently, construction activities have expanded to coastal areas as a
4 result of land reclamation projects in countries having limited land [1]. In this
5 connection, immense amounts of concrete ingredients, especially sand and freshwater,
6 are consumed which can eventually lead to gradual resources depletion unless new
7 sources are found. Furthermore, these material resources are not locally available and
8 the necessary transportation cost has incurred extra project expenses. A more
9 economical and innovative solution is to use marine sand and seawater as replacing
10 materials, since they are abundant in coastal region. The incorporation of marine sand
11 and seawater has already been practiced in concrete construction due to convenience in
12 extraction, reduced transportation need and hence cost saving [2, 3]. However, the
13 presence of salt content especially chloride can render steel corrosion of reinforced
14 concrete, produce cracks in concrete through expansion and subsequently cause
15 deterioration of the concrete. Therefore, to make full use of marine sand and seawater
16 successfully, appropriate methods have to be searched and developed to mitigate
17 corrosion issue in concrete.

18 To address corrosion issue, desalting treatment can be employed on marine sand and
19 seawater to reduce salt content to a threshold level [4]. This method is generally not
20 recommended in practice due to high operating cost and additional requirement of
21 exquisite quality control and management. Another more feasible remedy is to
22 incorporate mineral admixture that can improve concrete performance. Extensive
23 researches have shown that permeability of concrete can be minimized by adding
24 admixtures such as metakaolin and silica fume as they provide filling effect to refine
25 micro-pores in concrete [5, 6]. As such, corrosion of reinforcing steel in concrete can

1 be minimized as a result of lower oxygen ingress. Moreover, a more drastic method is
2 to replace conventional steel bars with non-corrodible reinforcement such as fiber
3 reinforced polymers [7, 8]. In this case, corrosion will not be an issue as corrodible steel
4 is absent.

5 As the application of marine sand and seawater in concrete is impeded by steel
6 corrosion, research on respective effect of these materials on concrete performance has
7 not attracted enough attention. These materials can, however, be used without much
8 refinement in mass concrete for foundation, maritime structure and retaining wall,
9 where steel reinforcement is not required. This leads to the need to further study effect
10 of marine sand and seawater in concrete. Several researches indicated that concrete
11 mixed with marine sand and seawater possessed higher early-age compressive and
12 tensile strengths, but exhibited slightly lower long-term strengths when compared to
13 normal concrete [3, 9]. Ogirigbo and Ukpata [10] found that chloride from marine sand
14 and seawater could react with cement hydrate to form Friedel's salt which promoted
15 early hydration of concrete. In addition, Islam et al. [11] reported 10% lower late-age
16 compressive strength due to gradual loss of hydration product caused by salt crystal
17 formation. Nevertheless, investigation carried out by Tjaronge et al. [12] showed that
18 concrete made with marine sand and seawater could achieve targeted 28-day
19 compressive strengths and also result in homogeneous compaction. In addition, Shi et
20 al. [5] found that seawater concrete exhibited higher compressive strength at all age. In
21 this regard, appropriate experiments are still required to iron out the discrepancy.

22 For durability of marine sand and seawater concrete, relatively less research has been
23 performed when compared to strength. The published literature generally showed that
24 marine sand had property to improve concrete durability [2, 13]. Huiguang et al. [2]
25 found that lower clay content of marine sand increased concrete resistance against

1 chloride penetration. Liu et al. [13] demonstrated that chloride from marine sand could
2 reduce concrete porosity and hence its carbonation resistance. As for concrete mixed
3 with seawater, pore structure analysis conducted by Tjaronge and Irfan [14] implied
4 that seawater could provide good bonding of cement matrix and aggregate. Shi et al. [5]
5 showed that concrete mixed with seawater exhibited better chloride penetration
6 resistance. However, limited research has been conducted in durability aspect
7 especially when marine sand and seawater are used together in concrete and as such,
8 further investigation is essential.

9 Apart from using locally available materials, incorporation of industrial waste in
10 producing concrete also has great advantage of lowering manufacturing cost.
11 Silicomanganese (SiMn) slag as shown in Figure 1 is a waste produced during
12 extraction of silicon and manganese metals from ores for use as alloying elements in
13 steel [15]. Production of SiMn is economically preferred and adapted because in this
14 extraction method, there is less loss of manganese as metal inclusion in steelmaking
15 [16]. As such, a large amount of wastes that include SiMn slag have been produced.
16 Statistics showed that the smelting plants from Samalaju Industrial Park in Malaysia
17 have already produced 400,000 tonnes of SiMn slag and these wastes are disposed of
18 through landfill [17]. This waste disposal method not only causes environmental
19 pollution, but also is costly and space-consuming. In the context of sustainability and
20 effective recycling of wastes, there is an urgency to carry out further research to utilize
21 SiMn slag. One feasible option is for it to be substituted as component in concrete.



1

2

Figure 1: Silicomanganese slag

3

To date, several researches have been performed to utilize SiMn slag as partial cement

4

replacement in concrete [18-20]. It was shown by Nath and Kumar [18] that concrete

5

incorporated with SiMn slag as partial cement replacement could achieve comparable

6

28-day compressive strength to normal concrete, though lower strength was observed

7

at early age. This was mainly due to inactive pozzolanic reaction of SiMn slag during

8

the early stage. Moreover, Frías et al. [20] found that cementitious paste blended with

9

cement and SiMn slag in small amount (5%-15%) could improve its resistance to

10

aggressive solutions like NaCl, Na₂SO₄ and seawater. The reason was that SiMn slag

11

could refine pore structure of cementitious mixture by filling up concrete void. From

12

the review, SiMn slag as cement replacement can yield good result. However, to

13

substitute SiMn slag for cement, additional grinding process is required which can

14

eventually increase production cost [21].

15

Therefore, it is more cost-effective if SiMn slag can directly be used as coarse aggregate

16

in concrete without undergoing extra treatment. There is limited investigation being

17

carried out using SiMn slag to replace gravel as coarse aggregate for concreting. Further

1 cost reduction can be made when locally available materials of marine sand and
2 seawater are utilized. From the perspective of sustainability and cost-effectiveness, full
3 replacement of the conventional materials is beneficial. Hence, in this investigation,
4 innovative concreting materials of SiMn slag, marine sand and seawater are used to
5 replace ordinary materials of gravel, river sand and tap water respectively. The aim of
6 this research is to study effect of the aforementioned materials on strength and
7 durability of concrete.

8 **2. Materials and methods**

9 *2.1. Materials characterization*

10 *2.1.1. Cement*

11 Ordinary Portland cement (OPC) graded as CEM 1 42.5 N was obtained from local
12 supplier, Cahaya Mata Sarawak (CMS) and used as binder in this research. It conformed
13 to the requirements stated in ASTM C150 [22].

14 *2.1.2. Coarse aggregate*

15 Coarse aggregates used in this research included crushed limestone (B1) and crushed
16 SiMn slag (B2) which had nominal sizes of 19.0 mm and 25.0 mm respectively. Particle
17 size distribution of the two types of aggregate is presented in Figure 2. Both aggregate
18 size distribution curves were within upper and lower bounds as specified in ASTM C33
19 [23]. Specific gravities of the aggregate B1 and B2 were determined as 2.64 and 2.97
20 respectively as presented in Table 1. Chemical composition of SiMn slag is shown in
21 Table 2.

22 *2.1.3. Fine aggregate*

23 Two types of sand, river sand and marine sand, were used as fine portion of aggregate
24 in concrete. The marine sand was sampled at Miri Tanjung Lobang Beach located in
25 Malaysia. Due to highly fine property of the sand, quarry dust retrieved from quarrying

1 waste was used to replace 30% sand by volume in order to ensure desirable concrete
2 workability. Particle size distributions of blended river sand (C1) and blended marine
3 sand (C2) together with upper and lower size distribution limits of ASTM C33 are
4 shown in Figure 2 [23]. Grading curve of C1 was close to the ASTM limit while it was
5 slightly beyond for C2 which indicated higher proportion of fine particle. The grading
6 of C2 aggregate can be further improved by blending with higher percentage of quarry
7 dust. However, it was not done due to economic reason and hence C2 aggregate was
8 still adopted for this study despite its non-conformation with recommended grading.

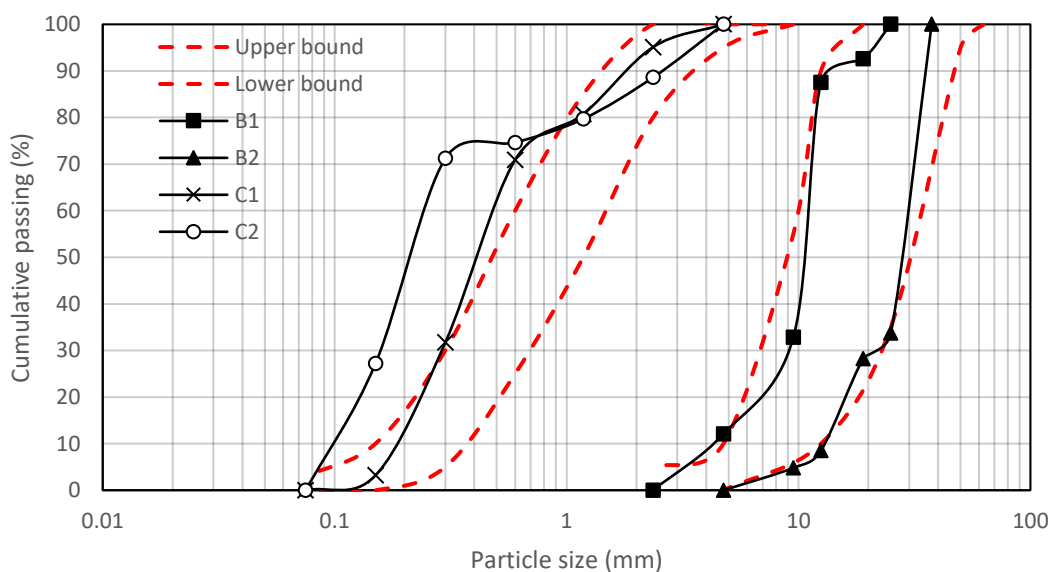
9 2.1.4. *Mixing water*

10 For mixing water, tap water (D1) and seawater (D2) were used. Table 3 summarizes
11 chemical composition of the seawater.

12 2.1.5. *Superplasticizer*

13 Superplasticizer (SP), sodium naphthalene sulphonate formaldehyde was used as
14 chemical admixture for ensuring sufficient workability of concrete.

15



16

17 **Figure 2: Particle size distribution of coarse and fine aggregates**

1

Table 1: Physical properties of aggregates

Properties of aggregates	B1	B2	C1	C2
Fineness modulus	6.75	9.25	3.18	2.59
Specific gravity	2.64	2.97	2.67	2.70
Water absorption (%)	0.66	0.21	-	-
Flatness ratio	0.68	0.55	-	-
Elongation ratio	0.68	0.59	-	-
Aschenbrenner & Zingg category	Equidimensional	Flaky and elongated	-	-

2

3

Table 2: Chemical composition of SiMn slag

Chemical composition	SiMn slag (%)
Silicon dioxide (SiO ₂)	41.49
Calcium oxide (CaO)	21.04
Aluminium oxide (Al ₂ O ₃)	13.95
Manganese oxide (MnO)	8.12
Magnesium oxide (MgO)	4.61
Ferric oxide (Fe ₂ O ₃)	4.47
Potassium oxide (K ₂ O)	1.35

4

5

Table 3: Chemical composition of seawater

Density (26 °C)	pH (26 °C)	Composition (mg/l)					
		Na	Mg	Ca	K	Cl	SO ₄
1.01 g/cm ³	8.1	17840	460	613	456	19675	1730

6

7 2.2. Mix proportion

8 Table 4 shows mix proportion designed for this study. Six types of concrete mixture

9 were proposed to study the influence of different materials on hardened concrete

10 properties. Hereafter, abbreviation of “Mix (B/C/D)” was used to indicate different type

11 of materials used for three components of concrete, whereby B denoted coarse

12 aggregate, C denoted fine aggregate and D denoted mixing water. Mix 1 (B1/C1/D1)

13 was control mix which contained conventional materials of limestone, river sand and

14 tap water as mixing ingredients. For all the mixes, water to cement ratio was kept

15 constant at 0.32. Besides, SP content used for all mixes was 1 %. The workability of

16 each mix was also examined through concrete slump test as summarized in Table 4.

1

Table 4: Mix proportion of concrete mixture

Components	Proportions (kg/m ³)					
	Mix 1 (B1/C1/D1)	Mix 2 (B2/C1/D1)	Mix 3 (B1/C2/D1)	Mix 4 (B1/C1/D2)	Mix 5 (B1/C2/D2)	Mix 6 (B2/C2/D2)
Cement	550	550	550	550	550	550
Limestone	965	0	965	965	965	0
SiMn slag	0	1115	0	0	0	1115
River sand	520	520	0	520	0	0
Marine sand	0	0	515	0	515	515
Quarry dust	167	167	173	167	173	173
Tap water	176	176	176	0	0	0
Seawater	0	0	0	176	176	176
Superplastizer	5.5	5.5	5.5	5.5	5.5	5.5
Slump value (mm)	121	77	89	82	88	78

Note:
B1 – Limestone, B2 – SiMn slag; C1 – River sand, C2 – Marine sand; D1 – Tap water, D2 – Seawater

2

3 2.3. Test methods

4 2.3.1. Compressive strength

5 Cylinder and cube compressive strengths were determined for each type of mix.
6 Cylindrical moulds having dimension of 100 mm x 200 mm and cube moulds of 100
7 mm were used respectively. The samples were cured for 7, 28 and 90 days and tested
8 by using 3000kN semi-auto compression testing machine in accordance with the
9 ASTM C39 requirement [24].

10 2.3.2. Splitting tensile strength

11 Splitting tensile test was used to evaluate concrete tensile strength. In carrying out the
12 test, cylindrical concrete samples with size of 100 mm x 200 mm were prepared. The
13 splitting tensile strengths of all mixes were measured at concrete ages of 7, 28 and 90
14 days. The samples were tested in accordance with the ASTM C496 requirement [25].

15 2.3.3. Water absorption and permeable pore

16 Water absorption and permeable pore volume of concrete were measured based on the
17 ASTM C642 test method [26]. 50 mm concrete cubes were prepared and tested at the
18 respective age of 28 and 90 days.

1 2.3.4. *Sorptivity*

2 Sorptivity test was conducted to measure rate of water absorption of concrete in
3 accordance with the ASTM C1585 requirement [27]. The test was carried out on
4 concrete samples after 28-day and 90-day curing. 100 mm x 200 mm cylindrical
5 samples were trimmed into dimension of 100 mm x 50 mm by using Covington slab
6 saw. The samples were then conditioned in oven for 7 days at 50 °C temperature. Side
7 and top surfaces of the samples were sealed while the bottom face was in contact with
8 water for absorption. Mass changes of the samples were measured for 8 days. Initial
9 and secondary sorptions were then calculated.

10 2.3.5. *Rapid chloride ion permeability*

11 Concrete permeability for each mix was also examined by performing rapid chloride
12 ion penetration test. The test procedure recommended by ASTM C1202 [28] was used
13 for this study. Cylindrical concrete samples with dimension of 100 mm x 50 mm were
14 prepared. The samples were cured for 28 and 90 days before the test. After standard
15 conditioning, the samples were connected to two cells, whereby one cell was filled with
16 3.0 % NaCl solution while the other cell contained 0.3 N NaOH solution. Electric
17 current which passed through the samples was measured for 6 hours and the
18 corresponding charge was determined. Table 5 showed the guideline for assessing
19 concrete permeability with respect to the flow charge.

20 **Table 5: Concrete permeability based on RCPT (ASTM C1202, 2012)**

Charge passed (coulombs)	Permeability of concrete
> 4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
100–1,000	Very low
< 100	Negligible

21

1 *2.3.6. Resistance to sulphate attack*

2 Sulphate immersion test was conducted for each concrete mix to evaluate its resistance
3 to sulphate attack. The test was conducted in accordance with the ASTM C1012
4 guideline [29]. 100 mm concrete cubes were casted, cured for 7 days and then immersed
5 in 5 % sodium sulphate solution for 7, 28 and 90 days. Concrete compressive strength
6 at each immersion durations was measured. Subsequently, reduction of the compressive
7 strength was determined.

8 **3. Results and discussions**

9 *3.1. Concrete workability*

10 Table 4 shows slump values which measure the workability of concrete of different
11 mixes. All the slump values were in the range of 77 mm to 121 mm which indicated
12 ample workability for concrete pumping [30]. Control mix, Mix 1 (B1/C1/D1) was
13 noted to exhibit the highest slump value. Meanwhile, incorporation of SiMn slag as
14 coarse aggregate replacement, as in Mix 2 (B2/C1/D1), reduced the slump value
15 significantly by 36 %. This was attributed to poor particle size distribution exhibited by
16 SiMn slag. Referring to Figure 2, approximately 70 % of SiMn slag aggregate was
17 retained on 25 mm sieve. Hence, there was a lack of finer particle to lubricate aggregate
18 skeleton for achieving desirable concrete workability. This research mainly focuses on
19 using 100 % SiMn slag in coarse aggregate replacement as it better utilizes industrial
20 by-product that can produce more sustainable and economic concrete. Nevertheless,
21 partial replacement of coarse aggregate by SiMn slag may result in well graded
22 aggregate and hence better workability. In this regard, further research is recommended
23 to confirm this finding.

24 Mix 3 (B1/C2/D1) concrete, manufactured with marine sand, showed 26 % lower slump
25 value compared with the control mix using river sand. This was due to fine property of

1 marine sand which possessed higher net particle surface area. This increased water
2 demand and hence additional water was required for achieving similar workability to
3 control concrete. Fineness modulus of marine sand and river sand were determined as
4 2.59 and 3.18 respectively, indicating lower average aggregate size exhibited by marine
5 sand. Mix 3 (B1/C2/D1) can achieve better workability by replacing marine sand with
6 more quarry dust as this increases fineness modulus of aggregate which exhibits less
7 water demand. Nevertheless, this will contribute to drawback of cost increase.

8 Replacement of tap water with seawater in Mix 4 (B1/C1/D2) showed 32 % lower
9 slump value than control mix. The result was in line with finding of Younis et al. [31]
10 that concrete mixed with seawater required extra 15 % superplasticizer to achieve
11 comparable workability to control concrete. The presence of salt in seawater reduces
12 concrete setting time whereby concrete losses its workability at higher rate.
13 Furthermore, the use of marine sand and seawater as in Mix 5 (B1/C2/D2) showed 27 %
14 reduction of slump value, while further incorporation of SiMn slag as in Mix 6
15 (B2/C2/D2) exhibited 36 % reduction. In short, although concrete incorporated with
16 SiMn slag, marine sand and seawater exhibited lower slump value, it can still provide
17 satisfactory workability in practice.

18 *3.2. Effect on compressive strength*

19 Cylinder and cube compressive strength of concrete at 7-day, 28-day and 90-day ages
20 is illustrated in Figure 3 and Figure 4 respectively. The compressive strength of all
21 concrete samples increased orderly with curing age. Both types of concrete strength
22 exhibited similar trend lines. By using the experimental data, relationship between
23 cylinder and cube compressive strengths was analyzed through linear regression
24 method. The resultant relationship is presented as Equation 1:

$$f_{cy} = 0.6945f_{cu} + 0.12 \quad \text{Equation 1}$$

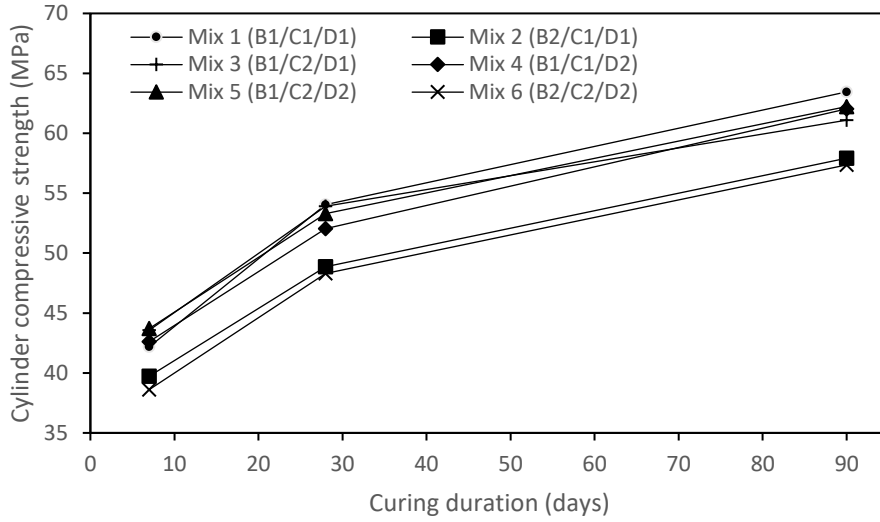
1 where f_{cy} and f_{cu} are cylinder and cube compressive strength respectively.

2 The cylinder strength was normalized by dividing it with the cube strength as illustrated
3 in Figure 5 and the cylinder to cube strength ratio was determined as 0.70. The result
4 was also compared well with British Standard and published literature. Concrete
5 strength ratio calculated from British Standard was 0.83 [32]. Meanwhile, Neville [33]
6 provided a more comprehensive cylinder and cube strength relationship which took into
7 consideration of various shapes and sizes of concrete samples and gave 0.61 strength
8 ratio. Also, Elwell and Fu [34] claimed that concrete cylinder to cube strength ratio
9 ranged from 0.60 and 0.90. Replacement of British Standard by Eurocode for concrete
10 design has advocated use of concrete cylinder strength rather than cube strength [35].
11 In this connection, Equation 1 can be beneficial in conversion of cube strength into
12 cylinder strength.

13 Table 6 presents variation of concrete compressive strength for all mixes with respect
14 to the control. Utilizing SiMn slag as coarse aggregate in concrete generally decreased
15 compressive strength regardless of age. Reduction of compressive strengths was
16 computed as 5.1 %, 8.0 % and 9.2 % at 7, 28 and 90 days respectively for Mix 2
17 (B2/C1/D1), while it was 7.6 %, 8.2 % and 8.3 % respectively for Mix 6 (B2/C2/D2).
18 As shown in Table 1, SiMn slag aggregate exhibited high flatness and elongation ratio
19 which was categorized as elongated and flaky aggregate, while limestone aggregate
20 belonged to equidimensional category. Therefore, the reduction of compressive
21 strength was attributed to angular shape and smoother surface of SiMn slag which
22 weakened its bonding with cement paste. Similar observation was reported in study
23 conducted by Kazjonovs, Bajare and Korjakins [36], whereby steel punch was used as

1 coarse aggregate. In this case, flaky steel punch exerted high and concentrated stress on
2 concrete interface which resulted in brittle failure at relatively low load.

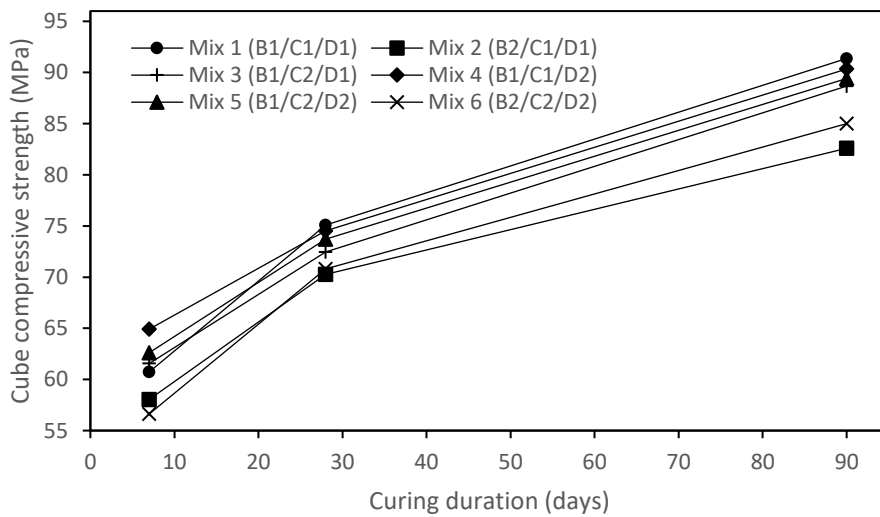
3 For concrete containing marine sand and seawater, as in Mix 3 (B1/C2/D1), Mix 4
4 (B1/C1/D2) and Mix 5 (B1/C2/D2), 7-day compressive strength increased by 2.3 %,
5 4.0 % and 3.4 % respectively. The strength increase can be attributed to formation of
6 Friedel's salt which resulted from reaction between free chloride and aluminate ferrite
7 monosulfate (AFm) hydrate [10, 37]. The Friedel's salt can fill up pores and provide
8 blocking effect which reduces concrete porosity and densifies pore structure. As a result,
9 the concrete exhibited higher strength. The results tied well with previous studies
10 performed by Katano et al. [3], Shi et al. [5] and Wegian [9], wherein higher early
11 strength was observed due to Friedel's salt. Meanwhile, for long-term compressive
12 strength, slight reduction was observed for all concrete mixes containing marine sand
13 and seawater. For example, the reductions at 90 days for Mix 3 (B1/C2/D1), Mix 4
14 (B1/C1/D2) and Mix 5 (B1/C2/D2) were 3.3 %, 1.7 % and 2.0 % respectively. The
15 strength deterioration was attributed to gradual crystallization of salt from marine sand
16 and seawater within concrete pore at the later age. Accumulation of salt crystals can
17 cause concrete expansion which develops micro-crack, resulting in strength reduction
18 [38]. The decrease of long-term strength caused by excessive salt content is verified by
19 sulphate salt immersion test, the results of which are presented later. Besides, Mix 6
20 (B2/C2/D2) concrete exhibited similar compressive strengths to Mix 2 (B2/C1/D1)
21 concrete at all ages. This implies that marine sand and seawater do not bring about
22 much negative effect to compressive strength on concrete batched with SiMn slag. As
23 such, there is potential for concrete manufactured with SiMn slag, marine sand and
24 seawater to be used for commercial purpose from perspective of compressive strength.



1

2

Figure 3: Development of cylinder compressive strength

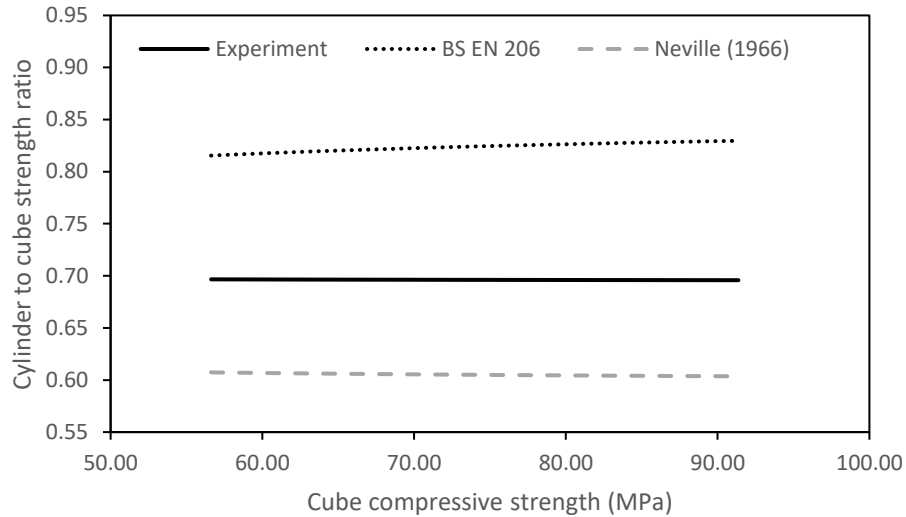


3

4

Figure 4: Development of cube compressive strength

5



1

2

Figure 5: Correlation between cylinder and cube compressive strength

3

Table 6: Strength variation with respect to control mix

Concrete age	Variation of compressive strength (%)				
	Mix 2 (B2/C1/D1)	Mix 3 (B1/C2/D1)	Mix 4 (B1/C1/D2)	Mix 5 (B1/C2/D2)	Mix 6 (B2/C2/D2)
7 days	-5.1	2.3	4.0	3.4	-7.6
28 days	-8.0	-1.9	-2.2	-1.6	-8.2
90 days	-9.2	-3.3	-1.7	-2.0	-8.3
Concrete age	Variation of splitting tensile strength (%)				
	Mix 2 (B2/C1/D1)	Mix 3 (B1/C2/D1)	Mix 4 (B1/C1/D2)	Mix 5 (B1/C2/D2)	Mix 6 (B2/C2/D2)
7 days	3.7	11.3	8.8	9.8	-11.8
28 days	-9.0	-3.6	-5.6	-3.7	-11.8
90 days	-17.5	3.7	-2.6	-4.9	-14.5

4

5 3.3. Effect on splitting tensile strength

6 Development of concrete splitting tensile for all mixes is presented in Figure 6. The
 7 results showed that the strength ranged from 3.6 MPa to 4.6 MPa, 4.6 MPa to 5.2 MPa
 8 and 5.2 MPa to 6.4 MPa at 7 days, 28 days and 90 days respectively. All the concrete
 9 tensile strength increased orderly with curing time.

10 Overall result showed reduction of splitting tensile strength in concrete manufactured
 11 with SiMn slag. At 90-day age, the strength reduction was 17.5 % and 14.5 % for Mix
 12 2 (B2/C1/D1) and Mix 6 (B2/C2/D2) respectively. Similar to compressive strength, the

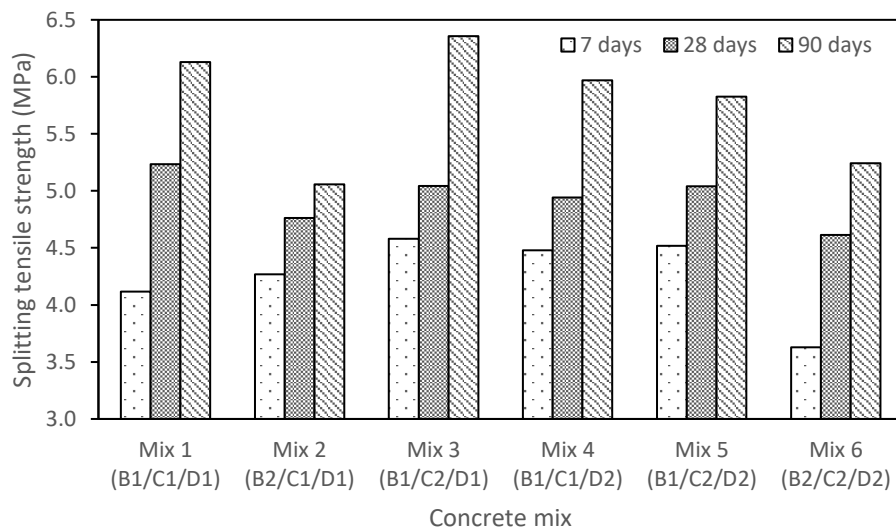
1 tensile strength decrease was due to flaky and elongated geometry exhibited by SiMn
2 slag which caused brittle and premature failure of concrete. It will be important that
3 future research is extended to develop methods to produce round shaped SiMn slag for
4 use as coarse aggregate in concreting. One possible method is by appropriate grinding
5 and then screening, but extra cost and time may be incurred. Moreover, another reason
6 was that smooth surface exhibited by SiMn slag had lessened adhesion and hence
7 bonding of aggregate with cement paste. The results are in accordance with findings
8 reported by Kazjonovs et al. [36] who used smooth steel punch as coarse aggregate.

9 Marine sand and seawater improved concrete splitting tensile strength at 7-day age by
10 11.3 %, 8.8 % and 9.8 % for Mix 3 (B1/C1/D2), Mix 4 (B1/C1/D2) and Mix 5
11 (B1/C2/D2) respectively. Similar to compressive strength, the strength increment at
12 early age was due to pore refinement promoted by Friedel's salt formation [10, 37].
13 Furthermore, Wegian [9] also showed that concrete mixed with and cured in seawater
14 possessed higher bonding strength and thus greater tensile strength. On long-term basis,
15 concrete containing marine sand and seawater achieved comparable tensile strength to
16 the control. Research performed by Wegian [9] and Limeira, Agullo and Etxeberria [39]
17 also indicated that marine sand and seawater had negligible effect on concrete tensile
18 strength at later age.

19 Generally, splitting tensile strength and compressive strength of concrete shows similar
20 result trend. In this connection, correlation between tensile and compressive strength is
21 established by using regression analysis based on experimental data. These two
22 parameters can be as expressed as a power function shown as Equation 2 below.

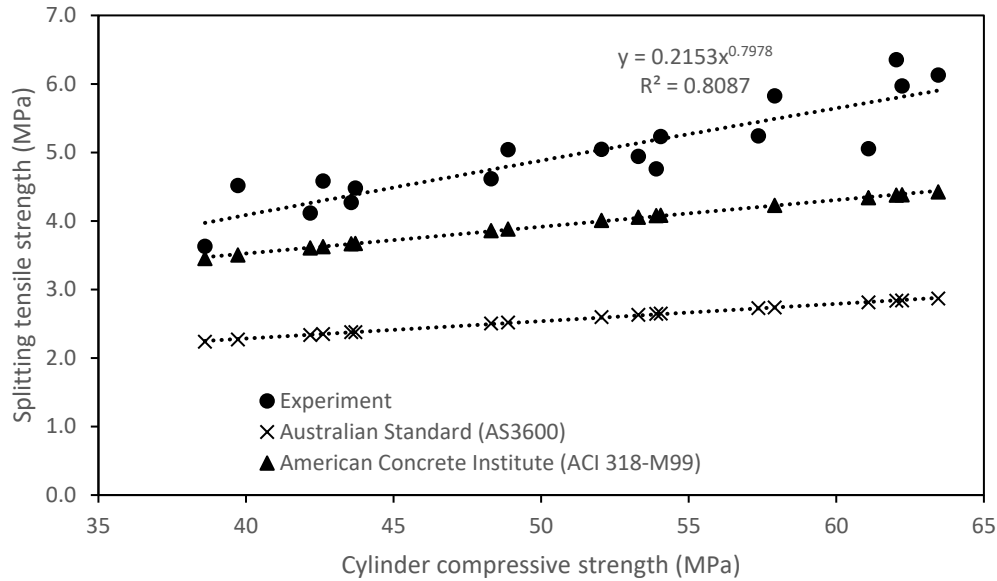
$$f_{ct} = 0.2153f_{cy}^{0.7978} \quad \text{Equation 2}$$

1 ,where f_{ct} is the splitting tensile strength and f_{cy} is the cylinder compressive strength.
 2 The computed relationship has an acceptable R^2 value of 0.81. To show validity of the
 3 equation, comparison is made with Australian Standard (AS) and American Concrete
 4 Institute (ACI) as depicted in Figure 7. The AS [40] provides a more conservative
 5 relationship between splitting tensile and compressive strength, while Equation 2 shows
 6 closer relationship to that in ACI [41]. This implies that incorporation of SiMn slag,
 7 marine sand and seawater has minimal effect on the relationship.



8

9 **Figure 6: Splitting tensile strength of concrete incorporating SiMn slag, marine**
 10 **sand and seawater**



1

2 **Figure 7: Correlation between splitting tensile and compressive strength**

3 *3.4. Water absorption and permeable pore of concrete*

4 Figure 8 presents water absorption and permeable pore volume of concrete at 28 and
 5 90 days. The water absorption ranged from 3.86 % to 5.30 % and 3.73 % to 4.78 % for
 6 28-day and 90-day ages respectively, while the concrete contained 11.25 % to 14.03 %
 7 and 10.79 % to 13.04 % pore volume respectively at these ages. The result generally
 8 indicated that water absorption increased with pore volume and vice versa. It also
 9 showed that water absorption and pore volume slightly decreased with concrete age.
 10 This was ascribed to more complete hydration of cement which produced increased
 11 calcium silicate hydrate (CSH) to fill up concrete pore.

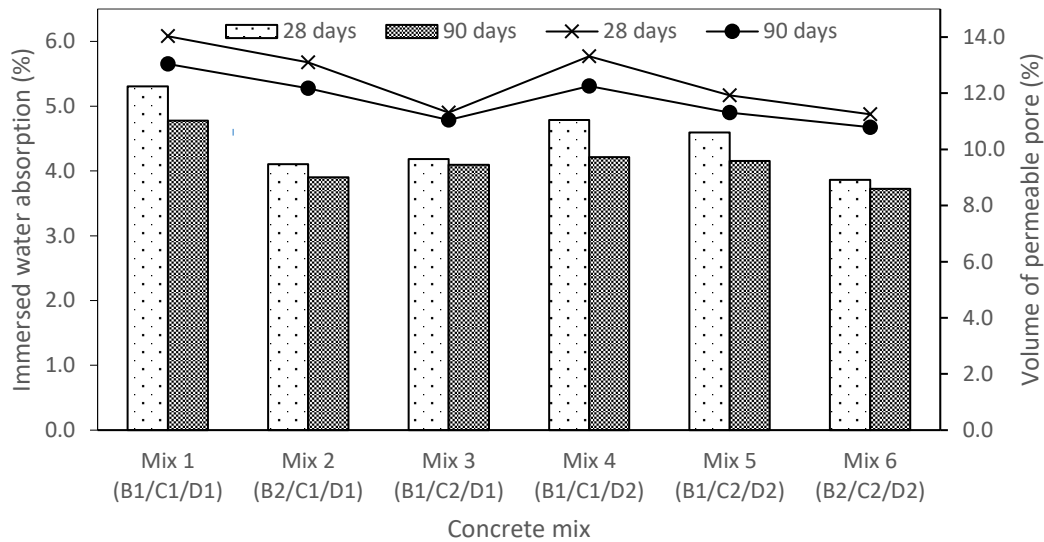
12 The use of SiMn slag significantly reduced water absorption of concrete. This was due
 13 to lower water absorption capability of SiMn slag aggregate. As shown in Table 1, the
 14 SiMn slag and limestone aggregates were found to possess 0.21 % and 0.66 % water
 15 absorption respectively. In this regard, SiMn slag aggregate retains less amount of water
 16 and hence the resultant concrete exhibits lower water absorption. As for pore volume,
 17 it was reduced for concrete containing SiMn slag as well. This indicated that reduction

1 of concrete water absorption was also attributed to lower porosity possessed by SiMn
2 slag concrete. Similar observation was made in study conducted by Alsayed and Amjad
3 [42], whereby natural and crushed aggregates were used. Although the obtained water
4 absorption values cannot effectively and directly measure concrete quality, they still
5 are below 10 % and hence within the range of good concrete defined by Neville [43].

6 Water absorption and pore volume of concrete containing marine sand, as in Mix 3
7 (B1/C2/D1), significantly decreased at both 28-day and 90-day ages. This was because
8 of smaller particle size possessed by marine sand. In this regard, the fine marine sand
9 can provide more densified microstructure. Cheng et al. [44] also showed that marine
10 sand minimized concrete porosity and hence capillary water absorption. For effect of
11 seawater, Mix 4 (B1/C1/D2) concrete exhibited slightly lower water absorption and
12 pore volume than the control. In alkaline environment of concrete, Friedel's salt could
13 precipitate from AFm hydrate and chloride which was stable in high pH and able to fill
14 concrete pore [5, 45, 46]. Although the study indicates that the porosity can be slightly
15 reduced by Friedel's salt, the effect on permeability is not significant as shown in
16 sorptivity test which will be explained and elaborated later. Also, effect of seawater is
17 not noticeable in Mix 5 (B1/C2/D2) as the pore refinement contributed by marine sand
18 is more dominant.

19 From the results and explanation presented so far, it is logical that concrete incorporated
20 with SiMn slag, marine sand and seawater exhibits the lowest water absorption and pore
21 volume, as confirmed by test result of Mix 6 (B2/C2/D2). Nevertheless, water
22 absorption and pore volume cannot best represent concrete durability as it only
23 indicates water retention capacity. In fact, rate of water absorption is a better indicator
24 of quality concrete. Therefore, concrete permeability has to be further assessed with

1 sorptivity and rapid chloride ion penetration tests, of which the results of these studies
 2 are presented in the following section.



3

4 **Figure 8: Immersed water absorption and volume of permeable pore of concrete**
 5 **incorporating SiMn slag, marine sand and seawater**

6 *3.5. Effect on sorptivity*

7 Sorptivity test which measures rate of water absorption can more precisely evaluate
 8 concrete permeability. Water absorption curves of concrete of all mixes at 28-day and
 9 90-day ages in this research are depicted in Figure 9(a) and Figure 9(b) respectively.
 10 The curves consist of two stages which include initial and secondary stages, whereby
 11 their slopes represent sorptivity of concrete as shown in Table 7. Initial sorptivity is
 12 greater as concrete pores are mostly empty at first and hence capillary flow occurs at
 13 faster rate, while the lower secondary sorptivity is due to slow filling of air void. As
 14 shown in the result, both types of sorptivity decreased with age for all concrete mixes.
 15 Similar to water absorption, more CSH was formed to densify concrete pore gradually
 16 as concrete aged.

1 Concrete casted with SiMn slag, as in Mix 2 (B2/C1/D1), exhibited higher sorptivity at
2 28-day age, but similar sorptivity at 90-day age when compared with control mix.
3 Higher sorptivity at 28-day age was due to weaker bonding of smooth SiMn slag with
4 cement matrix. According to Giaccio and Zerbino [47], coarse aggregate possessing
5 smooth surface will reduce concrete bonding strength and result in more porous
6 interface. As a result, water ingress is higher. As for the improved sorptivity at 90-day
7 age, it might be attributed to weak pozzolanic reaction occurring within interfacial
8 transition zone of the concrete. The mechanism of pozzolanic reaction involves
9 formation of calcium silicate hydrate (CSH) or calcium aluminate hydrate (CAH) from
10 reaction between calcium hydroxide and silicate or aluminate component [48]. Based
11 on test result in Table 2, SiMn slag comprised 41 % and 14 % of silicon dioxide and
12 aluminium oxide respectively. Although SiMn slag aggregate possesses relatively small
13 specific surface area, it is still possible that small scale pozzolanic reaction can take
14 place, especially on interface between the aggregate and cement paste. Study performed
15 by Masateru et al. [49] also showed that pozzolanic reaction which occurred on outer
16 layer of coal fly ash aggregate, could refine its interface with cement matrix. As a result,
17 some refinement may have been made on the concrete which reduces its porosity and
18 hence sorptivity. As the expected pozzolanic reaction only occurs on interface between
19 SiMn slag and cementitious matrix, which is relatively small-scale, improvement is not
20 reflected in the compressive strength of concrete. Nevertheless, further investigation
21 has to be carried out to confirm this finding.

22 The use of marine sand in Mix 3 (B1/C2/D1) significantly improved concrete durability
23 as its sorptivity reduced by nearly half at both 28-day and 90-day ages. This was
24 because marine sand aggregate was smaller in size which provided more compacted
25 concrete. Previous study conducted by Cheng et al. [44] showed that marine sand could

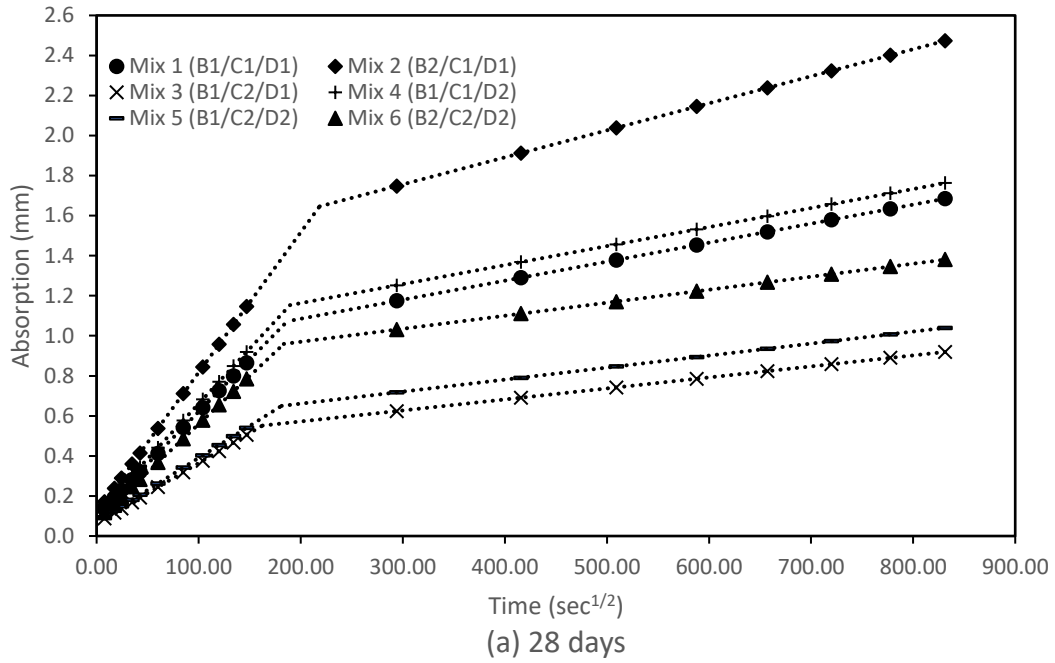
1 reduce porosity of cement paste, which optimized pore distribution, providing concrete
 2 with a denser microstructure. As shown in Mix 4 (B1/C1/D2), sorptivity of concrete
 3 mixed with seawater was almost the same as that of control mix. The result shows
 4 dissimilar effect as presented in the water absorption test. This implies that reduction
 5 of concrete porosity promoted by Friedel's salt is not adequate to improve its
 6 permeability as it is also dependent on pore characteristics such as pore size and
 7 connectivity. The effect on permeability may not be detected and reflected in the test
 8 as variations of water absorption and porosity are small. The result was also confirmed
 9 by Mix 5 (B1/C2/D2) whereby seawater was used for casting. As for Mix 6 (B2/C2/D2),
 10 the result showed the ability of marine sand to offset drawback of SiMn slag aggregate
 11 on concrete sorptivity at 28-day age and even improve it at 90-day age. Overall, the use
 12 of SiMn slag, marine sand and seawater can produce concrete with lower sorptivity and
 13 hence make it more durable than normal concrete.

14 **Table 7: Sorptivity at initial and secondary stages of concrete incorporating**
 15 **SiMn slag, marine sand and seawater**

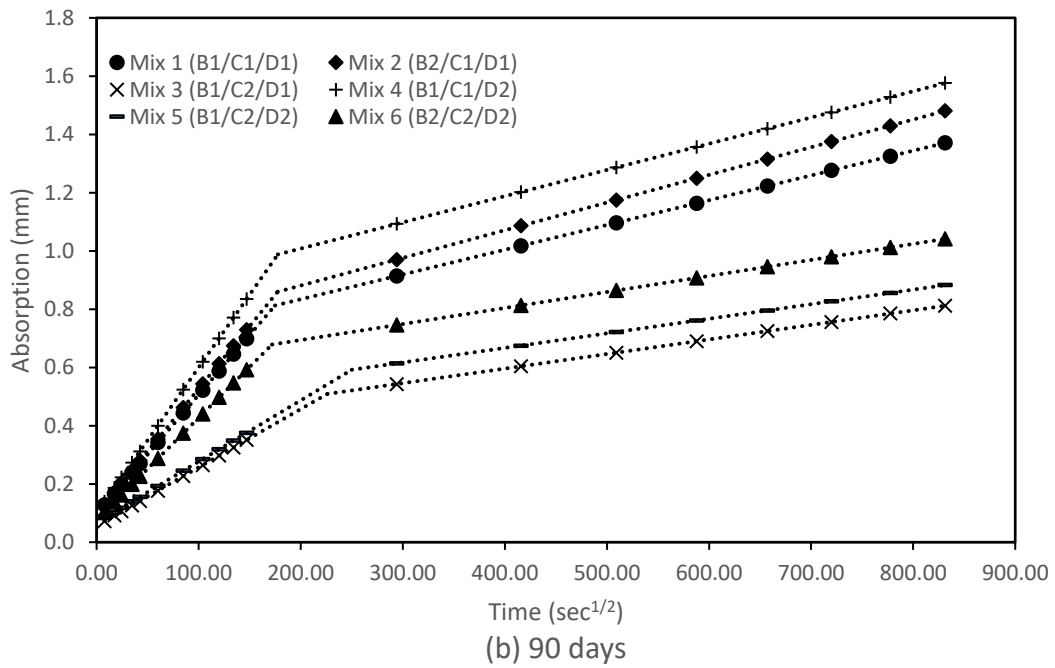
Mix	Initial sorptivity (mm/sec ^{1/2})	
	28-day	90-day
Mix 1 (B1/C1/D1)	0.0052	0.0041
Mix 2 (B2/C1/D1)	0.0070	0.0043
Mix 3 (B1/C2/D1)	0.0030	0.0020
Mix 4 (B1/C1/D2)	0.0055	0.0050
Mix 5 (B1/C2/D2)	0.0032	0.0021
Mix 6 (B2/C2/D2)	0.0048	0.0035
Mix	Secondary sorptivity (mm/sec ^{1/2})	
	28-day	90-day
Mix 1 (B1/C1/D1)	0.00095	0.00085
Mix 2 (B2/C1/D1)	0.00135	0.00095
Mix 3 (B1/C2/D1)	0.00055	0.00050
Mix 4 (B1/C1/D2)	0.00095	0.00090
Mix 5 (B1/C2/D2)	0.00060	0.00055
Mix 6 (B2/C2/D2)	0.00065	0.00055

16

17



1



2

3

Figure 9: Cumulative absorption of concrete

4

5 *3.6. Effect on rapid chloride ion penetration*

6 Alternatively, concrete permeability can also be measured based on its resistance to
 7 chloride ion penetration. Figure 10 summarizes chloride ion permeability of concrete

1 of all the mixes at 28-day and 90-day ages. At 28-day age, concrete chloride penetration
2 resistance which was measured as charge passed through it, ranged from 1885.6 to
3 2752.7 Coulomb (C). In this case, the concrete was graded as “moderate” permeability
4 except for Mix 3 (B1/C2/D1) and Mix 5 (B1/C2/D2) which were graded as “low”
5 permeability. Meanwhile, the charge which passed through 90-day concrete ranged
6 from 1421.8 to 1659.8 C and all concrete was classified as “low” permeability. This
7 showed that concrete resistance to chloride ion penetration improved with curing. This
8 was due to more complete hydration of cement which developed more CSH to fill
9 concrete pore.

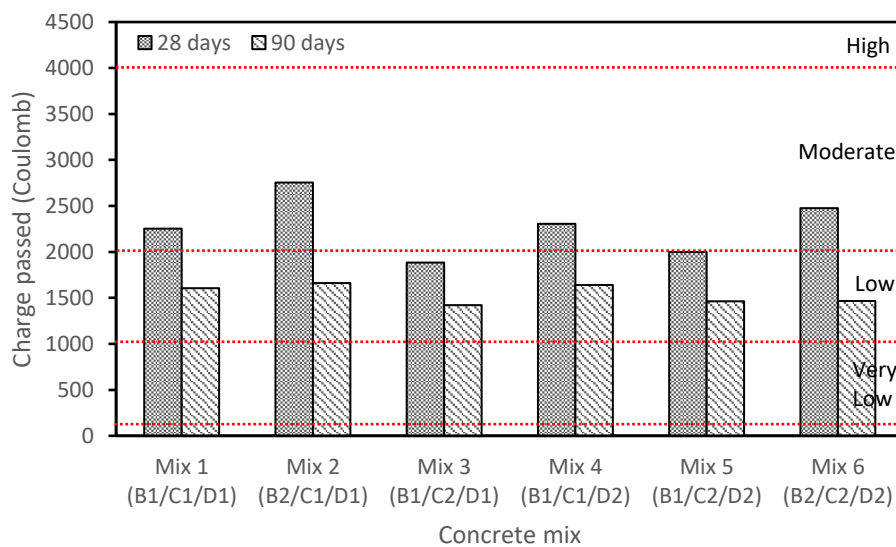
10 Mix 2 (B2/C1/D1) concrete which contained SiMn slag exhibited higher chloride
11 permeability at 28-day age, but it showed similar permeability to control concrete at
12 90-day age. The result showed same trend as that of sorptivity test. Similarly, same
13 explanation can be given to the improvement of concrete resistance to chloride ion
14 penetration at later age, whereby weak pozzolanic reaction might have occurred to
15 refine aggregate interface. In this case, chloride can also be bound onto extra CSH and
16 CAH which provides improved chloride binding capacity of concrete. Investigation by
17 Frías et al. [20] also showed that pozzolanic reaction resulted from SiMn slag enhanced
18 concrete resistance against penetration of aggressive chemicals such as chloride,
19 sulphate and seawater. Since both sorptivity and chloride penetration test results show
20 that SiMn slag concrete possesses comparable permeability to normal concrete on long
21 term, it has potential to be used commercially.

22 As observed in Mix 3 (B1/C2/D1), the use of marine sand improved concrete resistance
23 to chloride ion penetration at both 28-day and 90-day ages. The finer particle size of
24 marine sand reduced concrete pore volume and refined it into more compacted
25 microstructure. According to Cheng et al. [44], another possibility was that marine sand,

1 being more fine and having higher surface area, can retain more water to promote
 2 hydration through internal curing. As for seawater, the test result of Mix 4 (B1/C1/D2)
 3 showed that it had negligible effect on chloride permeability of concrete. This also
 4 implied that permeability reduction of Mix 5 (B1/C2/D2) concrete, which was made
 5 from both marine sand and seawater, was ascribed to effect of marine sand. As for Mix
 6 6 (B2/C2/D2), it had been shown that marine sand improved concrete resistance to
 7 chloride penetration as well.

8 In summary, test results of chloride ion permeability of all mixes agree well with those
 9 of sorptivity. It has been proven that using of the combination of SiMn slag, marine
 10 sand and seawater for concreting can result in more durable concrete than conventional
 11 concrete.

12



13

14 **Figure 10: Chloride ion permeability of concrete incorporating SiMn slag,**
 15 **marine sand and seawater**

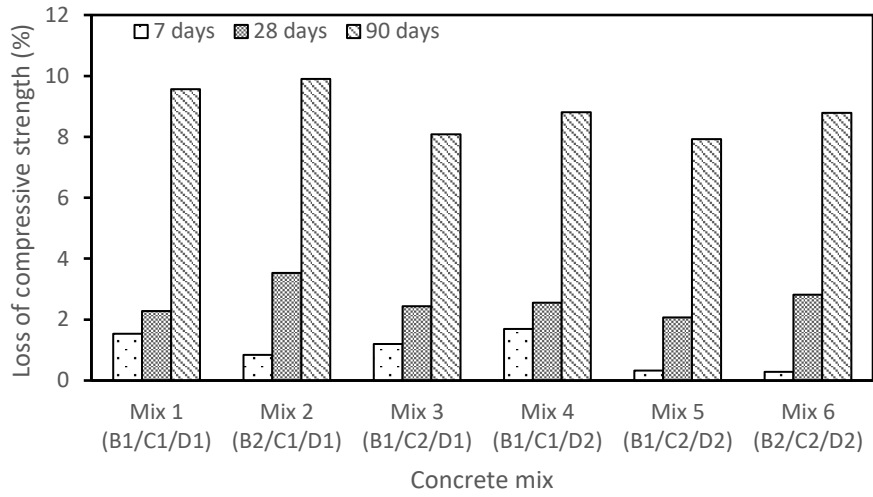
16

1 *3.7. Effect on resistance to sulphate attack*

2 Sulphate immersion test measures concrete resistance to sulphate attack in term of
3 compressive strength loss. Figure 11 depicts the loss of compressive strength for all
4 concrete mixes at 7-day, 28-day and 90-day immersion periods. It was observed that
5 loss of concrete compressive strength increased with immersion time. After 7 days of
6 immersion, the strength loss ranged from 0.28 % to 1.69 % which was negligible.
7 Meanwhile, strength loss after 28 days of immersion increased slightly to the range
8 between 2.07 % and 3.53 %. Concrete strength loss after 90 days of immersion, which
9 became more noticeable, was between 7.92 % and 9.90 %. The strength loss was due
10 to formation of expansive ettringite and gypsum from reaction between sulphate and
11 hydration products such as CAH and calcium hydroxide, which induced stress in
12 concrete [50]. Another deterioration mechanism was formation of salt crystal within
13 concrete pore which cause damage through expansion and subsequently concrete
14 micro-crack developed.

15 Although variation between the mixes was minimal, it had been observed that SiMn
16 slag exhibited slightly lower resistance to sulphate attack than the control for all
17 immersion duration. As the test was carried out after 7-day of curing, initial lower
18 hydration rate of SiMn slag concrete had made it more permeable to sulphate intrusion
19 which caused more damage. It was also shown in Mix 3 (B1/C2/D1), Mix 5 (B1/C2/D2)
20 and Mix 6 (B2/C2/D2) that marine sand could enhance concrete resistance to sulphate
21 attack. As explained previously, finer marine sand had produced concrete with lower
22 permeability that reduced sulphate ingress. Also, the result showed that seawater
23 slightly reduced concrete damage caused by sulphate attack. This was due to lower
24 porosity of the concrete contributed by Friedel's salt. On the whole, concrete

- 1 incorporated with SiMn slag, marine sand and seawater displayed slightly higher
- 2 resistance against sulphate attack.



3

4 **Figure 11: Loss of compressive strength for all concrete mixes**

1 **4. Conclusion**

2 The result of this experimental investigation has provided better insight into strength
3 and durability of concrete incorporating with SiMn slag, marine sand and seawater. In
4 this regard, the following conclusions can be drawn:

5 1. Incorporation of SiMn slag as coarse aggregate for concreting had reduced concrete
6 workability by 36 % due to poor aggregate size grading. Marine sand and seawater
7 also reduced concrete slump by 26 % and 32 % respectively.

8 2. With incorporation of SiMn slag, both compressive and tensile strength of concrete
9 had been reduced by as much as 9.2 % and 17.5 % respectively as flaky characteristic
10 of the aggregate had resulted in weaker bonding with cement paste. It was proven
11 that concrete manufactured with marine sand and seawater achieved higher strength
12 at early age, but lower late strength against the conventional concrete.

13 3. SiMn slag concrete exhibited lower water absorption, with value of 4.1 % and 3.9 %
14 at 28-day and 90-day ages respectively, against the control concrete with value of
15 5.3 % and 4.8 % at these ages, due to lower water absorption characteristic of SiMn
16 slag aggregate. Water absorption of the concrete can be further reduced to 3.9 % and
17 3.7 % at 28-day and 90-day ages respectively by incorporating with marine sand and
18 seawater which had characteristic to better fill up concrete pore.

19 4. Both sorptivity and rapid chloride penetration test results showed that incorporation
20 of SiMn slag increased concrete permeability at 28-day age when compared with
21 conventional concrete. However, similar permeability of two types of concrete was
22 shown by the tests at 90-day age. Also, the use of marine sand reduced concrete
23 permeability and was able to offset drawback of SiMn slag aggregate in the aspect
24 of durability.

1 5. Sulphate immersion test demonstrated that loss of concrete compressive strength due
2 to sulphate attack was small after 7-day and 28-day test periods. But, the loss became
3 more significant after 90-day immersion time with the highest loss value of 9.9 %.

4 Despite the limitation, it is possible to produce more durable concrete with
5 incorporation of SiMn slag, marine sand and seawater for potential industrial use. For
6 future research, it is necessary to carry out investigation to validate possible pozzolanic
7 reaction occurring at the out surface of SiMn slag aggregate.

8

1 **Acknowledgement**

2 The authors would like to express gratitude to the Curtin University for providing
3 laboratory support and Novakey Developer Sdn. Bhd for providing research fund. The
4 contribution and support from Dr Lau Hieng Ho at initial phase of this project is highly
5 appreciated by the authors.

6

7 **References**

- 8 [1] Limeira, J., L. Agulló, and M. Etxeberria, *Dredged marine sand as a new source*
9 *for construction materials*. *Materiales de Construcción*, 2012. **62**(305): p. 7-24.
- 10 [2] Huiguang, Y., L. Yan, L. Henglin, and G. Quan, *Durability of sea-sand containing*
11 *concrete: Effects of chloride ion penetration*. *Mining Science and Technology*
12 (China), 2011. **21**(1): p. 123-127.
- 13 [3] Katano, K., N. Takeda, Y. Ishizeki, and K. Iriya. *Properties and application of*
14 *concrete made with sea water and un-washed sea sand*. in *Proceedings of Third*
15 *International conference on Sustainable Construction Materials and Technologies*.
16 2013.
- 17 [4] Xiao, J., C. Qiang, A. Nanni, and K. Zhang, *Use of sea-sand and seawater in*
18 *concrete construction: current status and future opportunities*. *Construction and*
19 *Building Materials*, 2017. **155**: p. 1101-1111.
- 20 [5] Shi, Z., Z. Shui, Q. Li, and H. Geng, *Combined effect of metakaolin and sea water*
21 *on performance and microstructures of concrete*. *Construction and Building*
22 *Materials*, 2015. **74**: p. 57-64.
- 23 [6] Karthikeyan, M. and V. Nagarajan, *Feasibility study on utilization of marine sand*
24 *in concrete for sustainable development*. 2016.
- 25 [7] Li, L., B. Hou, Z. Lu, and F. Liu, *Fatigue behaviour of sea sand concrete beams*
26 *reinforced with basalt fibre-reinforced polymer bars*. *Construction and Building*
27 *Materials*, 2018. **179**: p. 160-171.
- 28 [8] Li, Y., X. Zhao, R.R. Singh, and S. Al-Saadi, *Tests on seawater and sea sand*
29 *concrete-filled CFRP, BFRP and stainless steel tubular stub columns*. *Thin-Walled*
30 *Structures*, 2016. **108**: p. 163-184.
- 31 [9] Wegian, F.M., *Effect of seawater for mixing and curing on structural concrete*.
32 *The IES Journal Part A: Civil & Structural Engineering*, 2010. **3**(4): p. 235-243.
- 33 [10] Ogirigbo, O.R. and J. Ukpata, *Effect of chlorides and curing duration on the*
34 *hydration and strength development of plain and slag blended cements*. *Journal of*
35 *Civil Engineering Research*, 2017. **7**(1): p. 9-16.
- 36 [11] Islam, M.M., M.S. Islam, M. Al-Amin, and M.M. Islam, *Suitability of sea water*
37 *on curing and compressive strength of structural concrete*. *J. Civil Eng*, 2012. **40**: p.
38 37-45.
- 39 [12] Tjaronge, M.W., R. Irmawaty, S.A. Adisasmita, and A. Amiruddin. *Compressive*
40 *Strength and Hydration Process of Self Compacting Concrete (SCC) Mixed with Sea*
41 *Water, Marine Sand and Portland Composite Cement*. in *Advanced Materials*
42 *Research*. 2014. Trans Tech Publ.

- 1 [13] Liu, W., H. Cui, Z. Dong, F. Xing, H. Zhang, and T.Y. Lo, *Carbonation of*
2 *concrete made with dredged marine sand and its effect on chloride binding.*
3 *Construction and Building Materials*, 2016. **120**: p. 1-9.
- 4 [14] Tjaronge, M.W. and U.R. Irfan, *Porosity, pore size and compressive strength of*
5 *self compacting concrete using sea water.* *Procedia Engineering*, 2015. **125**: p. 832-
6 837.
- 7 [15] Ding, W. and S.E. Olsen, *Manganese and silicon distribution between slag and*
8 *metal in silicomanganese production.* *ISIJ international*, 2000. **40**(9): p. 850-856.
- 9 [16] Olsen, S. and M. Tangstad, *Silicomanganese production - Process*
10 *understanding.* *Proceedings: Tenth International Ferroalloys Congress*, 2004: p. pp.
11 231-238.
- 12 [17] Wong, J., *Pertama eyes full capacity in October for smelting plant,* in *The Star*
13 *Online.* 2018, Star Media Group Berhad.
- 14 [18] Nath, S. and S. Kumar, *Evaluation of the suitability of ground granulated silico-*
15 *manganese slag in Portland slag cement.* *Construction and Building Materials*, 2016.
16 **125**: p. 127-134.
- 17 [19] Frias, M., M.I.S. de Rojas, J. Santamaría, and C. Rodríguez, *Recycling of*
18 *silicomanganese slag as pozzolanic material in Portland cements: basic and*
19 *engineering properties.* *Cement and Concrete Research*, 2006. **36**(3): p. 487-491.
- 20 [20] Frías, M., M.I.S. de Rojas, and C. Rodríguez, *The influence of SiMn slag on*
21 *chemical resistance of blended cement pastes.* *Construction and Building Materials*,
22 2009. **23**(3): p. 1472-1475.
- 23 [21] Kim, B.-S., S.-B. Jeong, M.-H. Jeong, and J.-W. Ryu, *Upgrading of manganese*
24 *from waste silicomanganese slag by a mechanical separation process.* *Materials*
25 *Transactions*, 2011. **52**(8): p. 1705-1708.
- 26 [22] *ASTM C150, Standard specification of Portland cement.* 2012, American Society
27 for Testing and Materials: West Conshohocken, PA.
- 28 [23] *ASTM C33, Standard specification for concrete aggregates.* 2012, American
29 Society for Testing and Materials: West Conshohocken, PA.
- 30 [24] *ASTM C39, Standard test method for compressive strength of cylindrical*
31 *concrete specimens.* 2012, American Society for Testing and Materials: West
32 Conshohocken, PA.
- 33 [25] *ASTM C496, Standard test method for splitting tensile strength of cylindrical*
34 *concrete specimens.* 2012, American Society for Testing and Materials: West
35 Conshohocken, PA.
- 36 [26] *ASTM C642, Standard test method for density, absorption and voids in hardened*
37 *concrete.* 2012, American Society for Testing and Materials: West Conshohocken,
38 PA.
- 39 [27] *ASTM C1585, Standard test method for measurement of rate of absorption of*
40 *water by hydraulic-cement concrete.* 2012, American Society for Testing and
41 Materials: West Conshohocken, PA.
- 42 [28] *ASTM C1202, Standard test method for electrical indication of concrete's ability*
43 *to resist chloride ion penetration.* 2012, American Society for Testing and Materials:
44 West Conshohocken, PA.
- 45 [29] *ASTM C1012, Standard test method for length change of hydraulic-cement*
46 *mortars exposed to a sulfate solution.* 2012, American Society for Testing and
47 Materials: West Conshohocken, PA.
- 48 [30] *ACI Committee 304. 1996. Placing concrete by pumping methods: (ACI 304.2R-*
49 *96).* American Concrete Institute: Farmington Hills, MI.

- 1 [31] Younis, A., U. Ebead, P. Suraneni, and A. Nanni, *Fresh and hardened properties*
2 *of seawater-mixed concrete*. Construction and Building Materials, 2018. **190**: p. 276-
3 286.
- 4 [32] British Standard Institution. 2000. *BS EN 206-1: Concrete specification,*
5 *performance, production and conformity*.
- 6 [33] Neville, A.M. *A general relation for strengths of concrete specimens of different*
7 *shapes and sizes*. in *Journal Proceedings*. 1966.
- 8 [34] Elwell, D.J. and G. Fu, *Compression testing of concrete: cylinders vs. cubes*.
9 1995.
- 10 [35] Mosley, W.H., R. Hulse, and J.H. Bungey, *Reinforced concrete design: to*
11 *Eurocode 2*. 2012: Macmillan International Higher Education.
- 12 [36] Kazjonovs, J., D. Bajare, and A. Korjakins. *Designing of high density concrete*
13 *by using steel treatment waste*. in *The 10th International Conference Modern building*
14 *materials, structures and techniques*. 2010.
- 15 [37] Shi, C., X. Hu, X. Wang, Z. Wu, and G.d. Schutter, *Effects of chloride ion*
16 *binding on microstructure of cement pastes*. Journal of Materials in Civil Engineering,
17 2016. **29**(1): p. 04016183.
- 18 [38] Zhang, J., M. Sun, D. Hou, and Z. Li, *External sulfate attack to reinforced*
19 *concrete under drying-wetting cycles and loading condition: numerical simulation*
20 *and experimental validation by ultrasonic array method*. Construction and Building
21 Materials, 2017. **139**: p. 365-373.
- 22 [39] Limeira, J., L. Agullo, and M. Etxeberria, *Dredged marine sand in concrete: An*
23 *experimental section of a harbor pavement*. Construction and Building Materials,
24 2010. **24**(6): p. 863-870.
- 25 [40] Standard Australia. 2018. *Concrete structures (AS 3600)*. SAI Global Limited.
- 26 [41] ACI Committee 318. 1999. *Building code requirements for structural concrete:*
27 *(ACI 318M-99)*. American Concrete Institute: Farmington Hills, MI.
- 28 [42] Alsayed, S.H. and M.A. Amjad, *Strength, water absorption and porosity of*
29 *concrete incorporating natural and crushed aggregate*. Journal of King Saud
30 University-Engineering Sciences, 1996. **8**(1): p. 109-119.
- 31 [43] Neville, A.M., *Properties of concrete*. Vol. 4. 1995: Longman London.
- 32 [44] Cheng, S., Z. Shui, T. Sun, R. Yu, and G. Zhang, *Durability and microstructure*
33 *of coral sand concrete incorporating supplementary cementitious materials*.
34 Construction and Building Materials, 2018. **171**: p. 44-53.
- 35 [45] Suryavanshi, A. and R.N. Swamy, *Stability of Friedel's salt in carbonated*
36 *concrete structural elements*. Cement and Concrete Research, 1996. **26**(5): p. 729-
37 741.
- 38 [46] Liu, J., K. Tang, Q. Qiu, D. Pan, Z. Lei, and F. Xing, *Experimental investigation*
39 *on pore structure characterization of concrete exposed to water and chlorides*.
40 Materials, 2014. **7**(9): p. 6646-6659.
- 41 [47] Giaccio, G. and R. Zerbino, *Failure mechanism of concrete: combined effects of*
42 *coarse aggregates and strength level*. Advanced Cement Based Materials, 1998. **7**(2):
43 p. 41-48.
- 44 [48] Sargent, P., *The development of alkali-activated mixtures for soil stabilisation*, in
45 *Handbook of alkali-activated cements, mortars and concretes*. 2015, Elsevier. p. 555-
46 604.
- 47 [49] Masateru, N., K. Masahiro, T. Takao, N. Kenji, and I. Yoshitaka, *Pozzolanic*
48 *Reactions between natural and Artificial Aggregate and the Concrete matrix*. 2007
49 World of Coal Ash (WOCA), 2007: p. 7-10.

1 [50] Tang, J., H. Cheng, Q. Zhang, W. Chen, and Q. Li, *Development of properties*
2 *and microstructure of concrete with coral reef sand under sulphate attack and drying-*
3 *wetting cycles*. *Construction and Building Materials*, 2018. **165**: p. 647-654.

4