Mechanical and Durability Performance of Marine Sand and Seawater Concrete Incorporating Silicomanganese Slag as Coarse Aggregate

Matthew Zhi Yeon Ting, Kwong Soon Wong, Muhammad Ekhlasur Rahman, Selowara Joo Meheron

Matthew Zhi Yeon Ting
Department of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University, Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia
Email: matthew.ting@postgrad.curtin.edu.my

Kwong Soon Wong (Corresponding author)
Department of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University, Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia
E-mail: wongkwongsoon@curtin.edu.my
Tel: +6085 443939
Fax: +6085 443837

Muhammad Ekhlasur Rahman
Department of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University, Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia
E-mail: merahman@curtin.edu.my

Meheron Selowara Joo
Department of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University, Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia
E-mail: meheron.sj@curtin.edu.my

Abstract

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

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

1. Introduction

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

To address corrosion issue, desalting treatment can be employed on marine sand and seawater to reduce salt content to a threshold level [4]. This method is generally not recommended in practice due to high operating cost and additional requirement of exquisite quality control and management. Another more feasible remedy is to incorporate mineral admixture that can improve concrete performance. Extensive researches have shown that permeability of concrete can be minimized by adding admixtures such as metakaolin and silica fume as they provide filling effect to refine micro-pores in concrete [5, 6]. As such, corrosion of reinforcing steel in concrete can be minimized as a result of lower oxygen ingress. Moreover, a more drastic method is to replace conventional steel bars with non-corrodible reinforcement such as fiber reinforced polymers [7, 8]. In this case, corrosion will not be an issue as corrodible steel is absent.

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

For durability of marine sand and seawater concrete, relatively less research has been performed when compared to strength. The published literature generally showed that marine sand had property to improve concrete durability [2, 13]. Huiguang et al. [2] found that lower clay content of marine sand increased concrete resistance against chloride penetration. Liu et al. [13] demonstrated that chloride from marine sand could reduce concrete porosity and hence its carbonation resistance. As for concrete mixed with seawater, pore structure analysis conducted by Tjaronge and Irfan [14] implied that seawater could provide good bonding of cement matrix and aggregate. Shi et al. [5] showed that concrete mixed with seawater exhibited better chloride penetration resistance. However, limited research has been conducted in durability aspect especially when marine sand and seawater are used together in concrete and as such, further investigation is essential.

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

Figure 1: Silicomanganese slag

To date, several researches have been performed to utilize SiMn slag as partial cement replacement in concrete [18-20]. It was shown by Nath and Kumar [18] that concrete incorporated with SiMn slag as partial cement replacement could achieve comparable 28-day compressive strength to normal concrete, though lower strength was observed at early age. This was mainly due to inactive pozzolanic reaction of SiMn slag during the early stage. Moreover, Frías et al. [20] found that cementitious paste blended with cement and SiMn slag in small amount (5%-15%) could improve its resistance to aggressive solutions like NaCl, Na_2SO_4 and seawater. The reason was that SiMn slag could refine pore structure of cementitious mixture by filling up concrete void. From the review, SiMn slag as cement replacement can yield good result. However, to substitute SiMn slag for cement, additional grinding process is required which can eventually increase production cost [21].

Therefore, it is more cost-effective if SiMn slag can directly be used as coarse aggregate in concrete without undergoing extra treatment. There is limited investigation being carried out using SiMn slag to replace gravel as coarse aggregate for concreting. Further cost reduction can be made when locally available materials of marine sand and seawater are utilized. From the perspective of sustainability and cost-effectiveness, full replacement of the conventional materials is beneficial. Hence, in this investigation, innovative concreting materials of SiMn slag, marine sand and seawater are used to replace ordinary materials of gravel, river sand and tap water respectively. The aim of this research is to study effect of the aforementioned materials on strength and durability of concrete.

2. Materials and methods

2.1. Materials characterization

2.1.1. Cement

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

2.1.2. Coarse aggregate

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

2.1.3. Fine aggregate

Two types of sand, river sand and marine sand, were used as fine portion of aggregate in concrete. The marine sand was sampled at Miri Tanjung Lobang Beach located in Malaysia. Due to highly fine property of the sand, quarry dust retrieved from quarrying waste was used to replace 30% sand by volume in order to ensure desirable concrete workability. Particle size distributions of blended river sand (C1) and blended marine sand (C2) together with upper and lower size distribution limits of ASTM C33 are shown in Figure 2 [23]. Grading curve of C1 was close to the ASTM limit while it was slightly beyond for C2 which indicated higher proportion of fine particle. The grading of C2 aggregate can be further improved by blending with higher percentage of quarry dust. However, it was not done due to economic reason and hence C2 aggregate was still adopted for this study despite its non-conformation with recommended grading.

2.1.4. Mixing water

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

2.1.5. Superplasticizer

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

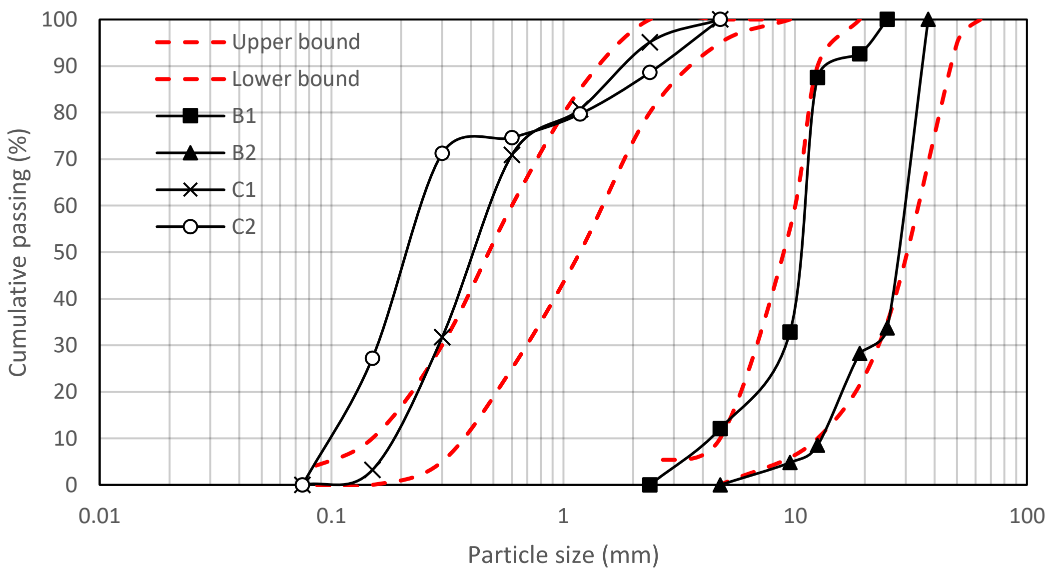


Figure 2: Particle size distribution of coarse and fine aggregates

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 catergory	Equidimensional	Flaky and elongated	-	-

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_2O_3)	13.95
Manganese oxide (MnO)	8.12
Magnesium oxide (MgO)	4.61
Ferric oxide (Fe_2O_3)	4.47
Potassium oxide (K_2O)	1.35

Table 3: Chemical composition of seawater

Density	pH	Composition (mg/l)					
(26 ºC)	(26 ºC)	Na	Mg	Ca	K	Cl	SO_4
1.01 g/cm^3	8.1	17840	460	613	456	19675	1730

2.2. Mix proportion

Table 4 shows mix proportion designed for this study. Six types of concrete mixture were proposed to study the influence of different materials on hardened concrete properties. Hereafter, abbreviation of "Mix (B/C/D)" was used to indicate different type of materials used for three components of concrete, whereby B denoted coarse aggregate, C denoted fine aggregate and D denoted mixing water. Mix 1 (B1/C1/D1) was control mix which contained conventional materials of limestone, river sand and tap water as mixing ingredients. For all the mixes, water to cement ratio was kept constant at 0.32. Besides, SP content used for all mixes was 1 %. The workability of each mix was also examined through concrete slump test as summarized in Table 4.

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. Test methods

2.3.1. Compressive strength

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

2.3.2. Splitting tensile strength

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

2.3.3. Water absorption and permeable pore

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

2.3.4. Sorptivity

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

2.3.5. Rapid chloride ion permeability

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

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

2.3.6. Resistance to sulphate attack

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

3. Results and discussions

3.1. Concrete workability

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

Mix 3 (B1/C2/D1) concrete, manufactured with marine sand, showed 26 % lower slump value compared with the control mix using river sand. This was due to fine property of marine sand which possessed higher net particle surface area. This increased water demand and hence additional water was required for achieving similar workability to control concrete. Fineness modulus of marine sand and river sand were determined as 2.59 and 3.18 respectively, indicating lower average aggregate size exhibited by marine sand. Mix 3 (B1/C2/D1) can achieve better workability by replacing marine sand with more quarry dust as this increases fineness modulus of aggregate which exhibits less water demand. Nevertheless, this will contribute to drawback of cost increase.

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

3.2. Effect on compressive strength

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

$$f_{cy} = 0.6945 f_{cu} + 0.12 \qquad \textbf{Equation 1}$$

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

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

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

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

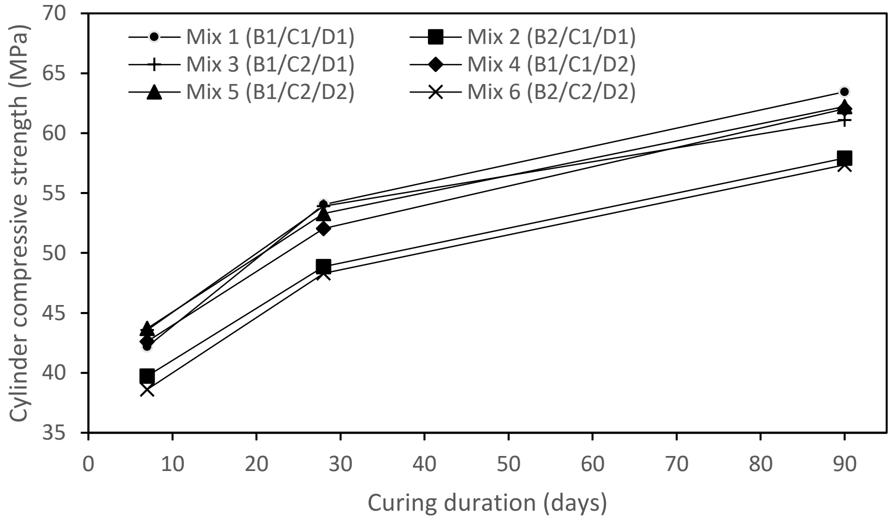


Figure 3: Development of cylinder compressive strength

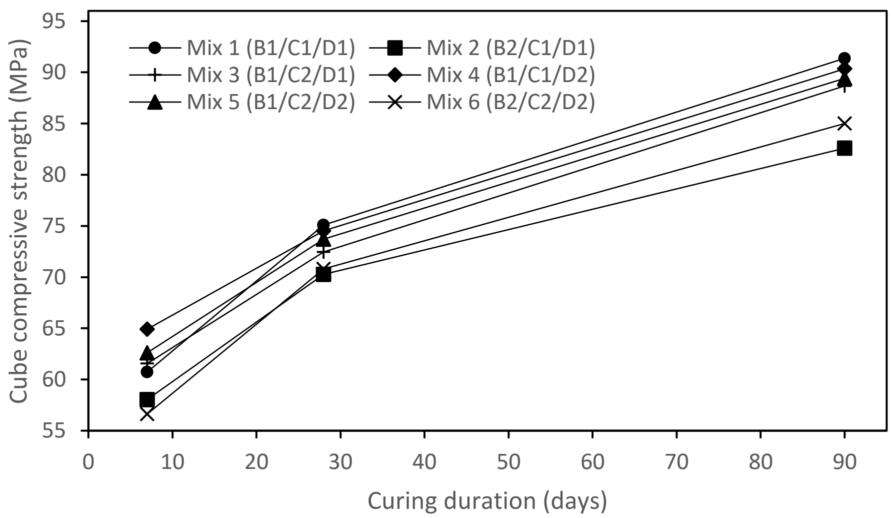


Figure 4: Development of cube compressive strength

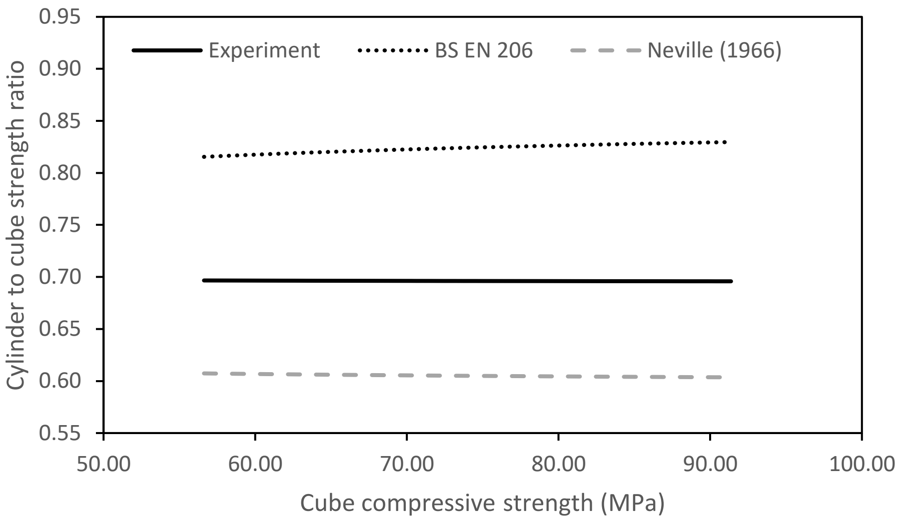


Figure 5: Correlation between cylinder and cube compressive strength

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

3.3. Effect on splitting tensile strength

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

Overall result showed reduction of splitting tensile strength in concrete manufactured with SiMn slag. At 90-day age, the strength reduction was 17.5 % and 14.5 % for Mix 2 (B2/C1/D1) and Mix 6 (B2/C2/D2) respectively. Similar to compressive strength, the tensile strength decrease was due to flaky and elongated geometry exhibited by SiMn slag which caused brittle and premature failure of concrete. It will be important that future research is extended to develop methods to produce round shaped SiMn slag for use as coarse aggregate in concreting. One possible method is by appropriate grinding and then screening, but extra cost and time may be incurred. Moreover, another reason was that smooth surface exhibited by SiMn slag had lessened adhesion and hence bonding of aggregate with cement paste. The results are in accordance with findings reported by Kazjonovs et al. [36] who used smooth steel punch as coarse aggregate.

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

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

$$f_{ct} = 0.2153 {f_{cy}}^{0.7978} \qquad \textbf{Equation 2}$$

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

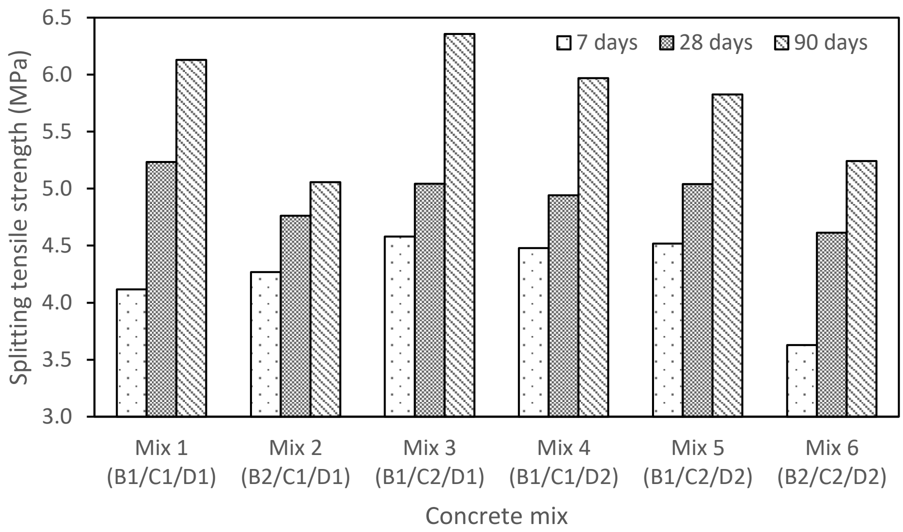


Figure 6: Splitting tensile strength of concrete incorporating SiMn slag, marine sand and seawater

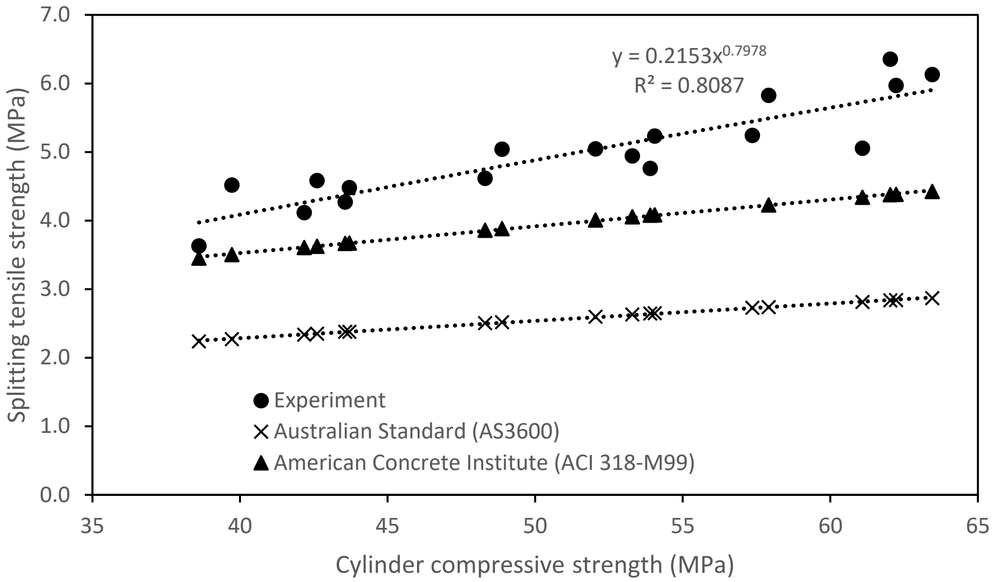


Figure 7: Correlation between splitting tensile and compressive strength

3.4. Water absorption and permeable pore of concrete

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

The use of SiMn slag significantly reduced water absorption of concrete. This was due to lower water absorption capability of SiMn slag aggregate. As shown in Table 1, the SiMn slag and limestone aggregates were found to possess 0.21 % and 0.66 % water absorption respectively. In this regard, SiMn slag aggregate retains less amount of water and hence the resultant concrete exhibits lower water absorption. As for pore volume, it was reduced for concrete containing SiMn slag as well. This indicated that reduction of concrete water absorption was also attributed to lower porosity possessed by SiMn slag concrete. Similar observation was made in study conducted by Alsayed and Amjad [42], whereby natural and crushed aggregates were used. Although the obtained water absorption values cannot effectively and directly measure concrete quality, they still are below 10 % and hence within the range of good concrete defined by Neville [43].

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

From the results and explanation presented so far, it is logical that concrete incorporated with SiMn slag, marine sand and seawater exhibits the lowest water absorption and pore volume, as confirmed by test result of Mix 6 (B2/C2/D2). Nevertheless, water absorption and pore volume cannot best represent concrete durability as it only indicates water retention capacity. In fact, rate of water absorption is a better indicator of quality concrete. Therefore, concrete permeability has to be further assessed with sorptivity and rapid chloride ion penetration tests, of which the results of these studies are presented in the following section.

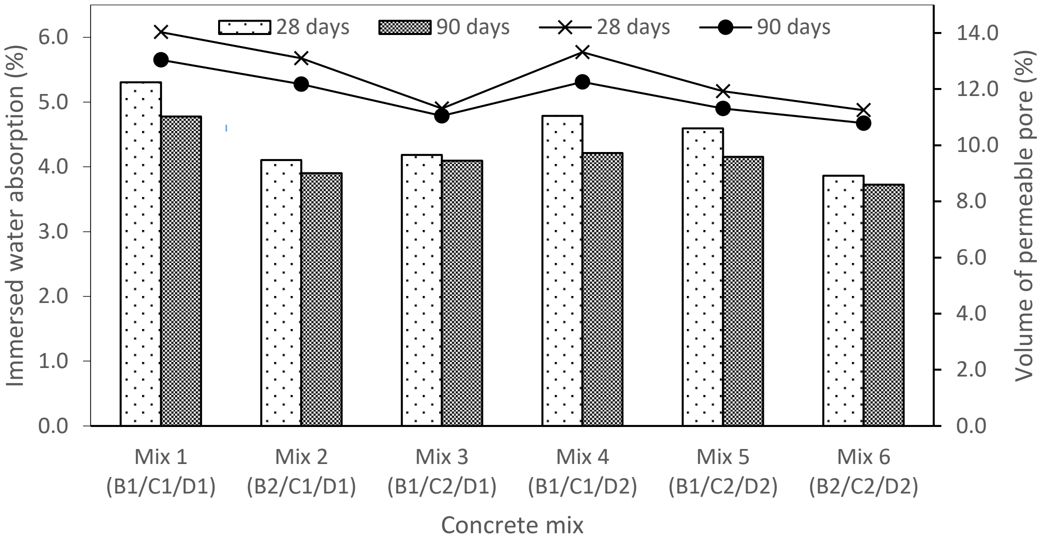


Figure 8: Immersed water absorption and volume of permeable pore of concrete incorporating SiMn slag, marine sand and seawater

3.5. Effect on sorptivity

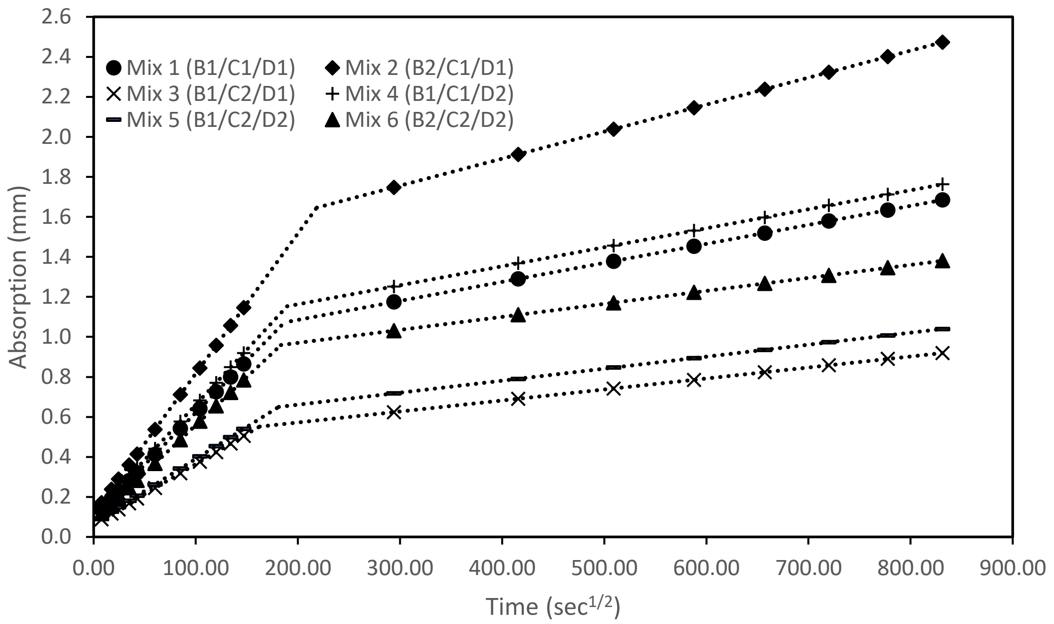
Sorptivity test which measures rate of water absorption can more precisely evaluate concrete permeability. Water absorption curves of concrete of all mixes at 28-day and 90-day ages in this research are depicted in Figure 9(a) and Figure 9(b) respectively. The curves consist of two stages which include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

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

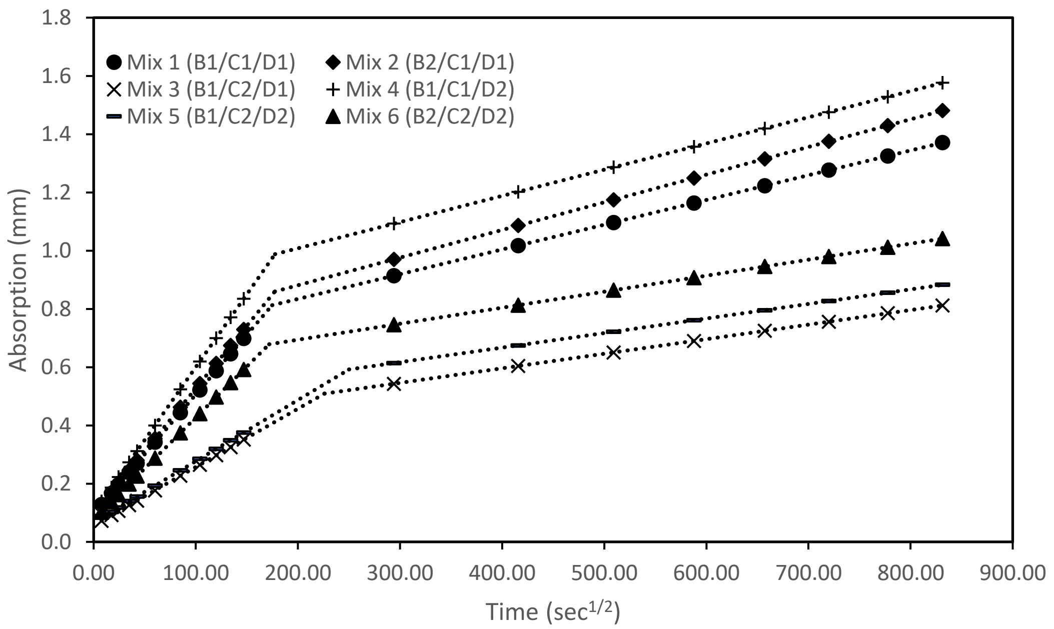
The use of marine sand in Mix 3 (B1/C2/D1) significantly improved concrete durability as its sorptivity reduced by nearly half at both 28-day and 90-day ages. This was because marine sand aggregate was smaller in size which provided more compacted concrete. Previous study conducted by Cheng et al. [44] showed that marine sand could reduce porosity of cement paste, which optimized pore distribution, providing concrete with a denser microstructure. As shown in Mix 4 (B1/C1/D2), sorptivity of concrete mixed with seawater was almost the same as that of control mix. The result shows dissimilar effect as presented in the water absorption test. This implies that reduction of concrete porosity promoted by Friedel's salt is not adequate to improve its permeability as it is also dependent on pore characteristics such as pore size and connectivity. The effect on permeability may not be detected and reflected in the test as variations of water absorption and porosity are small. The result was also confirmed by Mix 5 (B1/C2/D2) whereby seawater was used for casting. As for Mix 6 (B2/C2/D2), the result showed the ability of marine sand to offset drawback of SiMn slag aggregate on concrete sorptivity at 28-day age and even improve it at 90-day age. Overall, the use of SiMn slag, marine sand and seawater can produce concrete with lower sorptivity and hence make it more durable than normal concrete.

Table 7: Sorptivity at initial and secondary stages of concrete incorporating 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



(a) 28 days



(b) 90 days

Figure 9: Cumulative absorption of concrete

3.6. Effect on rapid chloride ion penetration

Alternatively, concrete permeability can also be measured based on its resistance to chloride ion penetration. Figure 10 summarizes chloride ion permeability of concrete of all the mixes at 28-day and 90-day ages. At 28-day age, concrete chloride penetration resistance which was measured as charge passed through it, ranged from 1885.6 to 2752.7 Coulomb (C). In this case, the concrete was graded as “moderate” permeability except for Mix 3 (B1/C2/D1) and Mix 5 (B1/C2/D2) which were graded as “low” permeability. Meanwhile, the charge which passed through 90-day concrete ranged from 1421.8 to 1659.8 C and all concrete was classified as “low” permeability. This showed that concrete resistance to chloride ion penetration improved with curing. This was due to more complete hydration of cement which developed more CSH to fill concrete pore.

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

As observed in Mix 3 (B1/C2/D1), the use of marine sand improved concrete resistance to chloride ion penetration at both 28-day and 90-day ages. The finer particle size of marine sand reduced concrete pore volume and refined it into more compacted microstructure. According to Cheng et al. [44], another possibility was that marine sand, being more fine and having higher surface area, can retain more water to promote hydration through internal curing. As for seawater, the test result of Mix 4 (B1/C1/D2) showed that it had negligible effect on chloride permeability of concrete. This also implied that permeability reduction of Mix 5 (B1/C2/D2) concrete, which was made from both marine sand and seawater, was ascribed to effect of marine sand. As for Mix 6 (B2/C2/D2), it had been shown that marine sand improved concrete resistance to chloride penetration as well.

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

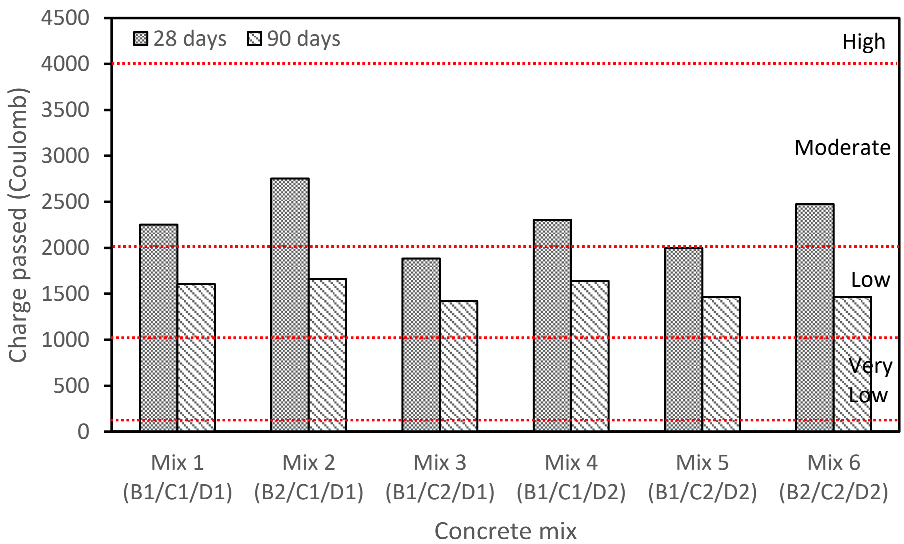


Figure 10: Chloride ion permeability of concrete incorporating SiMn slag, marine sand and seawater

3.7. Effect on resistance to sulphate attack

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

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

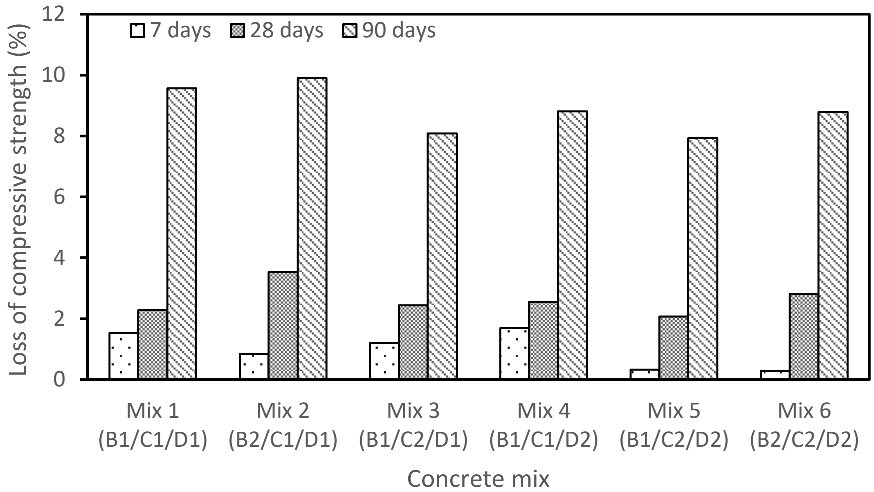


Figure 11: Loss of compressive strength for all concrete mixes

4. Conclusion

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

1. Incorporation of SiMn slag as coarse aggregate for concreting had reduced concrete workability by 36 % due to poor aggregate size grading. Marine sand and seawater also reduced concrete slump by 26 % and 32 % respectively.
2. With incorporation of SiMn slag, both compressive and tensile strength of concrete had been reduced by as much as 9.2 % and 17.5 % respectively as flaky characteristic of the aggregate had resulted in weaker bonding with cement paste. It was proven that concrete manufactured with marine sand and seawater achieved higher strength at early age, but lower late strength against the conventional concrete.
3. SiMn slag concrete exhibited lower water absorption, with value of 4.1 % and 3.9 % at 28-day and 90-day ages respectively, against the control concrete with value of 5.3 % and 4.8 % at these ages, due to lower water absorption characteristic of SiMn slag aggregate. Water absorption of the concrete can be further reduced to 3.9 % and 3.7 % at 28-day and 90-day ages respectively by incorporating with marine sand and seawater which had characteristic to better fill up concrete pore.
4. Both sorptivity and rapid chloride penetration test results showed that incorporation of SiMn slag increased concrete permeability at 28-day age when compared with conventional concrete. However, similar permeability of two types of concrete was shown by the tests at 90-day age. Also, the use of marine sand reduced concrete permeability and was able to offset drawback of SiMn slag aggregate in the aspect of durability.

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

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

Acknowledgement

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

References

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

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

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

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