Experimental investigations on the durability performance of normal concrete and engineered cementitious composite

I Komara1, P Suprobo1,*, D Iranata1, A Tambusay1, and W Sutrisno1

1 Department of Civil Engineering, Faculty of Civil, Planning and Geo Engineering, Sepuluh Nopember Institute of Technology, Surabaya, East Java, Indonesia.

*Corresponding author's e-mail: priyo@ce.its.ac.id

Abstract. This paper presents the experimental investigations in studying the durability performance of normal concrete and engineered cementitious composite (ECC) under varying key influencing factors. To this end, direct measurements on sorptivity, water absorption and rapid chloride penetration were undertaken for both normal concrete and ECC; each of which was tested using 67-mm thick sliced cylinder specimens with a diameter of 100 mm. The results from this studies highlight that the inherent low permeability properties in ECC are shown to provide excellent durability performance, in particular to the improvement of sorptivity rate and water absorption which is twice higher than that of normal concrete, indicating the very dense capillary pores microstructure. It is also found that chloride concentration on the surface of ECC is twice lesser than normal concrete, owing to the fact marginal manifestation of the electrical conductance.

1. Introduction
Concrete cracking is known to have a knock-on effect on the durability performance and long-term service life of reinforced concrete structures [1, 2]. This phenomenon is primarily attributed to complex loading conditions that may arise from external loading under day-to-day service in addition to environmental exposures, creating not only localised distress and stiffness degradation of structural members but also poor resistance of penetration from aggressive agents (e.g. alkali-silica reaction and chloride transport) which will result in further significant deterioration [6, 7].

Concrete cracking due to chemical reactions (i.e. chloride) is regarded as one of the most severe and aggressive deteriorations in marine infrastructure, particularly to concrete members subjected to wetting and drying cycles which are normally located in the splash zone [8-10]. Serious concrete deteriorations have been reported to date and it was found that the typical cause was mainly due to cracking, allowing for chloride to entrance to the level of steel bars easily. If the amount of chloride ingress is beyond the critical threshold concentration, pitting corrosion may be induced and propagates immensely, thereby causing spalling of concrete [11-14]. Aside from cracking, the durability of concrete also relies primarily on the ability of water to penetrate the microstructure of uncracked concrete. Water acts as the medium for corrosive agents (e.g. chloride ingress) and is mainly occurred through capillary absorption (sorptivity) and diffusion [15-17]. If the uncracked concrete has high porosity as in case of normal concrete, ingress of chloride may initiate the corrosion process through depassivation of steel bars and continue to accelerate the corrosion product in steel bars or also known as rust.
To avoid the premature deterioration, it is generally required to use a type of durable material in a sense that it is more relevant to the resistance of cracking in addition to being naturally less porous whilst in the uncracked state. With regard to this, there is a growing interest in the utilisation of cement-based composite as a means to offer durability improvement, such as enhanced pore microstructure, toughness and crack control. Engineered cementitious composite (ECC) is a special type of cementitious composite which is micro mechanically designed to exhibit high tensile strain capacity (in the order of a few percent) [17-20] and tight crack width control generally less than 0.1 mm [21, 22] (see figure 1). This material is regarded as having potential inherent durability and self-healing performance which thereby can be used to alleviate premature deterioration of marine infrastructure.

![Figure 1. Uniaxial tensile stress-strain relationship and crack widths of ECC [20].](image)

To confirm the suitability of ECC used in an aggressive environment, however, particularly under dry or partially saturated condition, research in the laboratory is necessary to perform. In this work, pilot study of experimental investigations on direct measurement of sorptivity, water absorption, and rapid chloride penetration of (uncracked) ECC specimens was undertaken; each of which represents the durability factor. Normal concrete specimens were also fabricated and measured in the same manner of ECCs to facilitate direct comparison on the extent of durability performance.

2. Experimental programme

2.1. Mixture proportion and fabrication

The mix proportions used to produce specimens for normal concrete and ECC are summarized in table 1 together with the results of 28-day mean compressive strengths. In normal concrete, the coarse aggregate from graded crushed granite was used and it had the maximum size of 10 mm. A well-graded fine aggregate with a size of less than 3 mm was also added into the mix. The binder for normal concrete comprised only of Portland cement referred to as CEMI-42.5R [23] with the water-to-cement ratio of 0.30 [24-26]. To ensure workability during mixing, a high-range water reducer (HRWR) superplasticiser was used with a dosage of 1.05 percent (by mass of cement). In ECC, a high volume of fine fly ash was added as a binder at a fly ash/cement ratio of 1.6/1 with the water-to-binder ratio of 0.28. The typical oxide analysis of Portland cement and fly ash are presented in tables 2 and 3 respectively. Unlike normal concrete, the sand used for ECC was silica sand in the form of powder with an average grain size of particles less than 0.1 mm. The fibre used for ECC was Kuralon RECS-15 polyvinyl alcohol (PVA) fibres, which were added into the matrix at a dosage of 2% by volume. The properties of PVA fibres are summarised in table 4.
Table 1. Mix proportions.

|                | CEM I (kg/m³) | 10 mm (kg/m³) | Fine (<3mm) (kg/m³) | Silica Sand (kg/m³) | Fly ash (kg/m³) | Water (kg/m³) | HRWR (kg/m³) | PVA (kg/m³) | Compressive Strength f’c (MPa) |
|----------------|---------------|----------------|---------------------|--------------------|----------------|--------------|-------------|------------|-------------------------------|
| NC             | 525           | 1054           | 764                 | 390                | 158            | 338          | 5.5         | 26         | 47.2                          |
| ECC            | 465           | -              | -                   | 744                | 325            | -            | 3.25        | 26         | 46.2                          |

Notes: NC is normal concrete; CEM I is Portland cement; 10 mm is coarse aggregate; HRWR is high-range water reducer; and PVA is polyvinyl alcohol.

Table 2. Oxide analysis of CEM I.

| Compound | Content (%) |
|----------|-------------|
| CaO      | 62.87       |
| SiO₂     | 20.33       |
| Al₂O₃    | 3.1         |
| Fe₂O₃    | 4.81        |
| MgO      | 0.1         |
| SO₃      | 2.5         |
| K₂O      | 0.45        |
| TiO₂     | 0.43        |
| V₂O₅     | 0.02        |
| CuO      | 0.075       |
| ZnO      | 0.027       |
| SrO      | 0.053       |
| ZrO₂     | 0.03        |
| BaO      | 0.06        |

Table 3. Oxide analysis of fly ash.

| Compound | Content (%) |
|----------|-------------|
| CaO      | 9.32        |
| SiO₂     | 43          |
| Al₂O₃    | 12.8        |
| Fe₂O₃    | 26.8        |
| MgO      | 0.17        |
| P₂O₅     | 0.81        |
| K₂O      | 2.36        |
| TiO₂     | 1.47        |
| V₂O₅     | 0.074       |
| Cr₂O₃    | 0.044       |
| CuO      | 0.05        |
| MoO₃     | 3           |
| BaO      | 0.25        |

Table 4. Properties of Kuralon RECS-15 PVA fibre.

| Type      | Fibre diameter (µm) | Length (mm) | Specific gravity (g/cm³) | Tensile strength (MPa) | Elongation (%) | Young’s modulus (GPa) |
|-----------|---------------------|-------------|--------------------------|------------------------|----------------|------------------------|
| RECS-15   | 40                  | 8           | 1.3                      | 1600                   | 6              | 41                     |

100-litre tilting drum mixer and 30-litre Hobart planetary motion mixer were used to cast normal concrete and ECC specimens respectively, and it was done in a single batch mixing. In normal concrete, dry materials were first mixed following the addition of water and HRWR. In ECC, however, a special treatment was devoted with care to ensure the successful mixing and uniform fibres dispersion. At the first stage of mixing, all dry materials (i.e. fly ash, cement and silica sand) were inserted into the bucket and were manually mixed using a wooden scoop. The mixing was done gently to prevent the release (loss) of fly ash particles and hence trap them under the cement and silica sand particles. 80% of water was then added and mixed manually with these dry materials. After the water was roughly mixed, the bucket was then moved to mixer machine and a low-speed mixing was applied to create a uniform smooth paste. Mixing was continued at medium speed for at least five minutes where the superplasticiser was added slowly following the remaining 20% of water. The gradual inspection was performed to ensure that the bottom deposit disappeared and had mixed up consistently. It was also of importance to ensure that the viscosity level was achieved. Upon this stage, low-speed mixing was set and fibres were poured into the fresh matrix slowly. Mixing speed was changed to a high-speed rate for approximately five minutes to let the fibres dispersed uniformly. The final inspection was done by gripping the fresh ECC with a hand for several times as a means of ensuring that there was no fibre ball occurred. Accordingly, the viscosity of fresh ECC was also evaluated using a marsh funnel cone.

The schematic representations of test specimens are displayed in figures 2(a) and (b). All test specimens were fabricated using a group of cylinder steel moulds with diameter and height of 100 by 200 mm, including cylinders used to define the compressive strengths. To confirm the quality of ECC
mixtures, additional fabrication was done on a series of dog-bone shaped (coupon) with geometry and dimensions following the JSCE recommendation [27] for direct tensile tests. The example of tensile stress-strain response of an ECC coupon alongside the crack pattern obtained using a recently developed low-cost automated crack mapping technique [28-30] is shown in figure 3. Upon casting, all normal concrete/ECC specimens were covered with plastic sheet and allowed to harden for 24 hours. The moulds were then dismantled and the specimens were stored in a curing tank at a room temperature until testing (28 days).

![Cylinder is cut into three parts](image1)

(a)

![Full field strain profile from DIC](image2)

(b)

**Figure 2.** Test specimens: (a) 100×200-mm cylinder and (b) ECC coupon.

**Figure 3.** Uniaxial tensile stress-strain relationship and DIC crack pattern of ECC.

2.2. Sorptivity, water absorption and chloride penetration tests

The sorptivity test was undertaken following the requirement per ASTM C1585 [31]. It is aimed to determine the rate of absorption through the increase of mass resulting from the absorption of water. The schematic setup of sorptivity test is displayed in figure 4. Prior to testing, a 100×200 mm cylinder made of concrete/ECC, which was stored at a temperature of 50 ± 2°C for three days after curing, was sliced into three equal parts (67-mm thick); each of which was weighed for mass measurement. The surfaces of the sliced specimens (except for the bottom side) were coated with waterproof epoxy. This was done to allow for absorption penetrating only from the bottom side of the specimen. The top and circumference surfaces of the specimen was also wrapped with plastic sheet to prevent evaporation due to environmental exposure. Upon this, the specimens were transferred to the dedicated tank and placed onto the supports. The absorption procedure was then conducted at 23 ± 2°C with tap water until reaching 1 to 3-mm level of water measured from the bottom surface of the specimen. The test involved the measurement of mass of cylinder specimens at given time intervals, which, in the case of work presented, at 1, 5, 10, 20, 30, 60, 120, 180, 240, 300 and 360 minutes at the first cycle following the successive measurement at 30 hours later for the second cycle with time intervals of 30, 54, 102, 126, 150 and 174 hours, allowing for water absorption through capillary suction. The rate of absorption was measured through the change in mass (gram) at the time divided by the cross-sectional area of the specimen (mm²) and the density of water (g/mm³).

The water absorption test was carried out in accordance with ASTM C642 [32] as a general means to obtain the percentage of absorption and voids in hardened concrete/ECC. In this test, the specimen was sliced in a similar manner with sorptivity specimens; however, it was dried inside the oven at a temperature of 100 to 110°C for at least 24 hours to determine the oven-dry mass of the specimen. The measurement was then taken after the removal from the oven at a temperature of 25°C. The oven-dry...
mass was compared with the initial mass of the specimen for control purposes until it reached the maximum difference value of 0.5%. Upon this procedure, the specimen was positioned in the container and immersed in the water at approximately 21°C for 174 hours until two successive values of mass at intervals of 24 hours showed an increase in mass of less than 0.5%, which hence define the saturated stage. It is worth noting that water absorption in this test could only take place in pores as a result of immersion process during testing. These pores could also be regarded as penetrable pores which are indicative of the degree of penetrability throughout the course of immersion until saturation.

The rapid chloride penetration test was undertaken based upon ASTM C1202-12 [33] to cover the evaluation of the electrical conductance of concrete and ECC for rapid indication of resistance due to penetration of chloride ions. The test involved 67-mm thick slice of 100-mm cross-sectional diameter of cylinders during 6-hour period. A potential difference of 60V in d.c. power supply was kept constant throughout testing; one of each was immersed in a 3% of sodium chloride (NaCl) solution, whilst the other in a 0.3N sodium hydroxide (NaOH) solution. The power supply cable connected to one side of specimen (immersed in NaCl) was treated as anode (-), whereas the other side which was immersed with NaOH was treated as cathode (+). The schematic setup of rapid chloride penetration test is displayed in figure 5.

3. Results and Discussion

3.1. Sorptivity

Figure 6 displays the relationship between the rate of capillary suction (sorptivity) and test time during the initial (first) and second cycle of mass measurement of three normal concrete and ECC specimens, with the detailed values of absorption summarised in tables 5 and 6 respectively. The cumulative mass of water absorption plotted against the test time is also depicted in figure 7.
With reference to figure 6, it is apparent that, in general, the rate of sorptivity is shown to increase as the test time is increased. During the first (initial) cycle of measurement, it can be seen that the typical rate of sorptivity in normal concrete specimens increases linearly with relatively high increment (steep line) up to 60 minutes. Dissimilar response is found in ECC specimens, in which the extent of increment is more insignificant. As the test time is continued to increase (i.e. circa 60 to 100 minutes), a noticeable spike of rate is evident in normal concrete specimens, whilst the ECCs still exhibit a minor linear-like increase. As the test time is further increased (beyond 100 minutes), the increase of sorptivity rate of normal concrete and ECC specimens becomes consistent up to the end of the second cycle measurement.

With regard to the progression of water absorption measured in the experiment, the comparison obviously demonstrates that water penetrates faster in normal concrete as a result of inherent porosity in its microstructural properties. It is also evidenced from table 5 that the final sorptivity rate of normal concrete is 0.5 which is 40% (almost twice) higher than that of ECC (see table 6 for comparison). This certainly highlights the excellent durability performance of ECC specimens. It is worth mentioning that this manifestation is primarily attributed to the fact that ECC is structured with micro materials and tailored in such a way that it provides excellent resistance of absorption in addition to its strain hardening behaviour.

With regard to figure 7, it is evident that both normal concrete and ECC specimens exhibit comparable additional (cumulative) mass in the early stage of test time (i.e. up to 5 minutes). As the time is continued, water penetrates more drastically on normal concrete but still in linear (steep) increase, whilst in ECC, the response starts to deviate from linearity, creating a significant gap with normal concrete as the increase of mass in ECC is relatively trivial. The results obtained from water absorption tests indicate a reasonable trend as in case of sorptivity rate and it is evident that from the overall cumulative mass measured, ECC demonstrates the lower water absorption index. The average peak mass of three cylinder ECC specimens is at a value of 22 grams, whereas the normal concrete escalates considerably to a value of 42 grams which is approximately two times higher than ECC.
The comparison of the percentage of water absorption on three uncracked normal concrete and ECC specimens is presented in Table 7. The mass of oven-dry specimen (labelled A) shown in the table was measured after the specimen was stored in the oven for 24-hour periods which also had 0.5% deviation with the initial mass (before stoved). The mass of immersed specimen (labelled B) was obtained after
full immersion with water at testing time of 174 hours (or 7 days) which was measured directly after the removal of surface moisture with fabric material (i.e. towel). The results obtained generally indicate the presence of water ingress which is trapped inside the capillary structures of normal concrete and ECC. Of interest is the percentage of water absorption in ECC specimens which is significantly lesser than normal concrete, signifying once again the excellency of ECC in terms of durability performance. It is also evident in the table that the percentage obtained in ECC is twice lesser than the normal concrete which is indicative of low permeability properties.

Table 7. Summary of percentage of water absorption.

| Sample | Diameter (cm) | Height (cm) | Initial mass (g) | 24-h oven-dry mass, A (g) | 174-hr mass after immersion, B (g) | Percentage of absorption after immersion (%) |
|--------|---------------|-------------|------------------|--------------------------|-----------------------------------|---------------------------------------------|
| NC1    | 10.07         | 6.635       | 1240.29          | 1230.18                  | 1285.42                           | 3.9                                         |
| NC2    | 10.07         | 6.63        | 1136.17          | 1132.22                  | 1179.83                           | 3.6                                         |
| NC3    | 10.07         | 6.7         | 1192.49          | 1190.13                  | 1236.94                           | 3.5                                         |
| ECC1   | 10.02         | 6.4         | 962.55           | 961.32                   | 988.59                            | 2.0                                         |
| ECC2   | 10.02         | 6.9         | 1129.5           | 1128.7                   | 1155.03                           | 1.4                                         |
| ECC3   | 10.02         | 6.7         | 986.94           | 985.36                   | 1012.83                           | 2.0                                         |

Note: NC is normal concrete specimen

3.3. Rapid chloride penetration

The rapid chloride penetration test is widely known as one of the most important factors in defining the durability performance of concrete due to the ingress of corrosive (chloride) agent. The qualitative indications of chloride ion penetrability are determined based on the classification of charge passed (coulombs) as presented in Table 8. The charge passed (coulombs), \( Q \), is calculated based on the trapezoidal rule with the expression described in the following manner [33],

\[
Q = 900(I_0 + 2I_{30} + 2I_{60} + \cdots + 2I_{300} + 2I_{330} + I_{360})
\]

where \( I_0 \) is the current (amperes) immediately after voltage is applied and \( I_t \) is the current (amperes) at \( t \) (minutes) after the voltage is applied.

Table 8. Classification of chloride ion penetrability based on charge passed [33].

| Charge passed (coulombs) | Chloride ion penetrability |
|--------------------------|---------------------------|
| > 4000                   | High                      |
| 2000–4000                | Moderate                  |
| 1000–2000                | Low                       |
| 100–1000                 | Very Low                  |
| < 100                    | Negligible                |

Table 9 presents the records of current of normal concrete and ECC specimens during testing period at given time intervals, along with the summary of total charge passed (coulombs). The current (amperes) transmitted into the specimen is resulted from the electrical conductance through NaCl and NaOH solutions. These two solutions obviously have major key roles to play while migrating into the concrete/ECC as they serve as a medium to conduct electricity through ions. From the table presented, it is evident that the chloride penetration in normal concrete is considerably higher which is marked by the extent of charge passed at an average value of 2007 C, underlining the moderate level of chloride ion penetrability. On the contrary, ECC exhibits the marginal average value of charge passed (i.e. 981 C) which is indicative of very low level of chloride ion penetrability. The marginal manifestation of electrical conductance in ECC is found to be affected by the presence of polymeric admixtures, allowing for the improvement of durability. This finding is also aligned with the ability of ECC to provide slow water absorption and sorptivity as highlighted in the previous sections.
Aside from the rapid chloride penetration, chloride diffusion (migration) coefficient is also considered important to be addressed herein as it provides the critical information of chloride ions speed penetrating in the concrete and ECC. Diffusion coefficient is determined by measuring the concentration of chloride ions on the surface of the cylinder specimen after the rapid chloride penetration and is calculated using these following expressions [34],

\[
D = \frac{RTL}{zFE} \left( \frac{x_d - \alpha \sqrt{x_d}}{t} \right)
\]  
\[
\alpha = 2 \sqrt{\frac{RT}{zFE}} \text{erf}^{-1} \left( 1 - \frac{2C_d}{C_0} \right)
\]
\[
E = \frac{U - 2}{L}
\]

where \(D\) is the non-steady-state chloride diffusion coefficient \((\text{m}^2/\text{sec})\); \(R\) is gas constant \((=8.314 \text{ (J/(°K mol)})\)); \(T\) is the average (absolute) value of the initial and final temperature (K); \(z\) is the absolute value of chloride ion \((=1); F\) is Faraday constant \((=9.648 \times 10^4 \text{ (J/(V mol)})\)); \(E\) is the electric field (V/m); \(U\) is the absolute value of the applied voltage (V); \(L\) is the thickness of the specimen (m); \(x_d\) is the average value of the penetration depth (m); \(\alpha\) is laboratory constant \((\text{m}^{1/2})\) calculated based on equation 2(b); \(t\) is test duration (sec); \(\text{erf}^{-1}\) is the inverse of error function; \(C_d\) is chloride concentration at which the colour changes \((\text{mol/dm}^3); \text{and } C_0\) is chloride concentration in cathode solution \((\text{mol/dm}^3)\).

### Table 9. Summary of charge passed (coulombs) recorded at 30-min interval.

| Specimen  | Current (amperes) | Normal concrete | ECC |
|-----------|------------------|-----------------|-----|
| No.       | 1                | 2               | 3   | 1    | 2    | 3    |
| 0         | 0.05             | 0.05            | 0.04| 0.04 | 0.04 | 0.04 |
| 30        | 0.06             | 0.06            | 0.05| 0.04 | 0.04 | 0.04 |
| 60        | 0.06             | 0.07            | 0.06| 0.04 | 0.04 | 0.04 |
| 90        | 0.07             | 0.07            | 0.07| 0.04 | 0.04 | 0.04 |
| 120       | 0.08             | 0.08            | 0.08| 0.04 | 0.04 | 0.04 |
| 150       | 0.09             | 0.09            | 0.09| 0.05 | 0.04 | 0.04 |
| 180       | 0.09             | 0.09            | 0.1 | 0.05 | 0.04 | 0.04 |
| 210       | 0.1              | 0.1             | 0.1 | 0.05 | 0.05 | 0.05 |
| 240       | 0.11             | 0.11            | 0.11| 0.05 | 0.05 | 0.05 |
| 270       | 0.11             | 0.11            | 0.11| 0.05 | 0.05 | 0.05 |
| 300       | 0.12             | 0.12            | 0.12| 0.05 | 0.05 | 0.05 |
| 330       | 0.13             | 0.13            | 0.13| 0.05 | 0.05 | 0.05 |
| 360       | 0.14             | 0.13            | 0.14| 0.05 | 0.05 | 0.05 |
| Q (C)     | 2007             | 2016            | 1998| 999  | 963  | 981  |
| Mean (C)  | 2007             |                 | 1998| 999  | 963  | 981  |

### Table 10. Summary of chloride diffusion coefficient.

| C_0 (%) | C_d (%) | T (K) | RT zFE | x_d (m) | t (sec) | \alpha (-) | D (m^2/s) |
|---------|---------|-------|--------|---------|---------|------------|-----------|
| NC      | 3       | 1.34  | 303    | 2.25 \times 10^{-5} | 0.01 | 21600 | 7.56 \times 10^{-5} | 1.04 \times 10^{11} |
| ECC     | 3       | 0.84  | 303    | 2.17 \times 10^{-5} | 0.01 | 21600 | 1.96 \times 10^{-3} | 9.85 \times 10^{12} |

Note: NC is normal concrete specimen.
Table 10 summarises the comparison of chloride diffusion coefficients (in the form of chloride ions speed, $D$ (m$^2$/sec)) between normal concrete and ECC specimens, which are calculated using equations 2(a)-(c). From the table presented, it is apparent that a slightly higher diffusion coefficient is found in normal concrete with a mean value of $1.04 \times 10^{-11}$ m$^2$/sec which is 5.5% greater than that of ECC (i.e. $9.85 \times 10^{-12}$ m$^2$/sec). Although the difference of diffusion coefficient is marginal, it is worth mentioning that the concentration of chloride ($C_d$) on the surface of normal concrete is found to be twice higher than ECC, which means that normal concrete suffers considerably during chloride ingress process.

4. Concluding remarks
The results of experimental investigation dealing with direct measurements of durability factors are presented to address the influence of sorptivity, water absorption, and rapid chloride penetration on (uncracked) normal concrete and ECC specimens. Systematic tests on these three parameters were thoroughly undertaken in the laboratory following the procedures and recommendations from the adopted codes. From the experimental results presented, it can be concluded that the sorptivity rate of ECC in the first and second cycle is shown to produce gradual increase which is in contrast with the response of normal concrete. A similar response is also found in the water absorption tests where ECC generally exhibits a considerably lesser percentage of water absorption when compared against normal concrete. In the rapid chloride penetration test, very low chloride ion penetrability level is also measured in ECC, whilst normal concrete exhibits moderate level which is indicative of high porosity inherent properties. The test results are now confirmed that ECC is shown to provide high durability performance, making it suitable to be utilised in aggressive environmental conditions such as for marine infrastructure.

Acknowledgements
The authors wish to acknowledge the support from Laboratory of Concrete, Advanced Materials and Computational Mechanics of Sepuluh Nopember Institute of Technology and PT. Wijaya Karya Beton Tbk. for supplies of Portland cement and fly ash. The first author wishes to acknowledge the financial support from Indonesia Endowment Fund for Education of the Ministry of Finance under LPDP scholarship programme. Thanks also to G.J.P Ghewa for his assistance in the experimental work.

References
[1] Li M and Li V C 2011 Cracking and healing of engineered cementitious composites under chloride environment *ACI Mater. J.* 108, 333–40
[2] Castro J, Spragg R and Weiss J 2013 Crack-healing investigation in bituminous materials *J. Mater. Civ. Eng.* 25, 864–70
[3] Kim J, McCarter W J, Suryanto B, Nanukuttan S, Basheer P A M and Chrisp T M 2016 Chloride ingress into marine exposed concrete: a comparison of empirical and physically-based models *Cem. Concr. Compos.* 72 133–45
[4] Alaswad G, McCarter W J and Suryanto B 2018 Moisture movement within concrete exposed to simulated hot arid/semi-arid conditions *Proc. Inst. Civ. Eng. - Constr. Mater.* 1–15
[5] Maalej M, Chhoa C Y and Quek S T 2010 Effect of cracking, corrosion and repair on the frequency response of RC beams *Constr. Build. Mater.* 24, 719–31
[6] Strauss A, Wendner R, Bergmeister K and Costa C 2013 Numerically and experimentally based reliability assessment of a concrete bridge subjected to chloride-induced deterioration *J. Inf. Sys.* 19 2 166–175
[7] Sahmaran M, Li M and Li V C 2007 Transport properties of engineered cementitious composites under chloride environment *ACI Mater. J.* 104 6 604–11
[8] Cao C and Cheung M M S 2014 Non-uniform rust expansion for chloride-induced pitting corrosion in RC structures *Constr. Build. Mater.* 51 p. 75–81
[9] Berrocal C G, Lundgren K and Löfgren I 2016 Corrosion of steel bars embedded in fibre reinforced concrete under chloride attack: state of the art *Cem. Concr. Res.* 80 69–85
[10] Maalej M, Ahmed S F U and Paramasivam P 2003 Corrosion durability and structural response of functionally-graded concrete beams *J. Adv. Concr. Technol.* 1, 307–16
[11] Kim J, McCarter W J and Suryanto B 2018 Performance assessment of reinforced concrete after long-term exposure to a marine environment Constr. Build. Mater. 192 569–83
[12] Yu K, Li L, Yu J, Wang Y, Ye J and Xu Q F 2018 Direct tensile properties of engineered cementitious composites: a review Constr. Build. Mater. 165 346–62
[13] Kelham S, 1988 A water absorption test for concrete Mag. Concrr. Res. 40 106–10
[14] Booya E, Gorospe K, Ghaednia H and Das S 2019 Durability properties of engineered pulp fibre reinforced concretes made with and without supplementary cementitious materials Compos. Part B Eng. 172 376–86
[15] Suryanto B, Saraireh D, Kim J, McCarter W J, Starrs G and Taha H M 2017 Imaging water ingress into concrete using electrical resistance tomography Int. J. Adv. Eng. Sci. Appl. Math. 9, 2 109–18
[16] Li V C and Kanda T 1998 Engineered cementitious composites for structural applications J. Mater. Civ. Eng. 10 66–69
[17] Suryanto B, McCarter W J, Wilson S A and Chrisp T M 2016 Self-healing performance of engineered cementitious composites under natural environmental exposure Adv. Cem. Res. 28 211–20
[18] Komara I, Tambusay A, Sutrisno W and Suprobo P 2019 Engineered Cementitious Composite as an innovative durable material: a review ARPN J. Eng. Appl. Sci. 14, 822–33
[19] Tambusay A, Suprobo P, Faimun and Amiruddin A, 2017 Finite element analysis on the behavior of slab-column connections using PVA-ECC material J. Tekn. 79 5 22–32
[20] Tambusay A 2017 Cyclic Behaviour of Slab-Column Connections using the Engineered Cementitious Composite PhD Thesis Institut Teknologi Sepuluh Nopember, Surabaya
[21] Suryanto, B, Wilson S A, McCarter W J 2015 Self-healing of micro-cracks in engineered cementitious composites Civ. Eng. Dimens. 17 187–93
[22] Suryanto B, McCarter W J, Starrs G, Wilson S A and Traynor R M 2015 Smart cement composites for durable and intelligent infrastructure Proc. Eng. 125, 796–803
[23] DIN EN 197-1 Special cement composition and conformity evaluation 2000
[24] Mooy M, Tambusay A, Komara I, Sutrisno W, Faimun F and Suprobo P 2020 Evaluation of shear-critical reinforced concrete beam blended with fly ash IOP Conf. Ser. Earth Environ. Sci. 506 012041
[25] Bastian M A, Tambusay A, Komara I, Sutrisno W, Irawan D and Suprobo P 2020 Enhancing the ductility of a reinforced concrete beam using engineered cementitious composite IOP Conf. Ser. Earth Environ. Sci. 506 012044
[26] Oktaviani W N, Tambusay A, Komara I, Sutrisno W, Faimun F and Suprobo P 2020 Flexural behaviour of a reinforced concrete beam blended with fly ash as supplementary material IOP Conf. Ser. Earth Environ. Sci. 506 012042
[27] JSCE 2008 Recommendations for design and construction of high performance fiber reinforced cement composite with multiple fine cracks, Japan Society of Civil Engineers
[28] Tambusay A, Suryanto B and Suprobo P 2020 Digital image correlation for cement-based materials and structural concrete testing Civ. Eng. Dimens. 22 1 6–12
[29] Suryanto B, Tambusay A and Suprobo P 2017 Crack mapping on shear-critical reinforced concrete beams using an open source digital image correlation software Civ. Eng. Dimens. 19 2 93–8
[30] Tambusay A, Suryanto B and Suprobo P 2018 Visualization of shear cracks in a reinforced concrete beam using the digital image correlation Int. J. Adv. Sci. Eng. Inf. Technol. 8 2 573–78.
[31] ASTM C1585-13 2013 Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes ASTM Int. (United States: West Conshohocken)
[32] ASTM C642-13 2013 Standard test method for density, absorption, and voids in hardened concrete ASTM Int. (United States: West Conshohocken)
[33] ASTM C1202-12 2012 Standard test method for electrical indication of concrete’s ability to resist chloride ion penetration ASTM Int. (United States: West Conshohocken)
[34] Zych T 2014 Test method of concrete resistance to chloride ingress Resist. Concr. to Chloride Ingress 6-B 117–39