

Sorptivity of self-compacting concrete with high volume fly ash and its eco-mechanical-durability performance

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Abstract. The durability of concrete is governed by the ability of the concrete to resist the penetration of aggressive agents from the environment. The capillary pores of concrete play an important role in the absorption of water, through which aggressive agents may enter into the body of concrete. The rate and amount of absorbed water can be measured by the sorptivity test. It is also recognised that the composition of concrete itself influences the pore structure of the concrete. Hence, in a non-conventional concrete with a very different mixture such as self-compacting concrete (SCC) incorporating a high volume of fly ash, the sorptivity is expected to be different from that of the concrete. This paper aims to determine the influence of high volume fly ash contents on the sorptivity of SCCs, as measured by the method of ASTM C1858. The balanced performance of the concrete – in terms of ecological, mechanical, and durability performance – is assessed using the eco-mechanical-durability index (*EMDI*). The index is developed as a combined value of eco-mechanical index (*EMI*) and eco-durability index (*EDI*). The sorptivity is adopted as the durability parameter in developing the *EDI*. The results confirm that an optimum value of sorptivity at an early age is obtained when about 55% of the OPC is replaced with fly ash. At a later age, however, the optimum value is changed to the 65% replacement level. A higher volume of fly ash tends to decrease the *EMI* but increase the *EDI*. Consequently, the effect of fly ash content on *EMDI* depends on the relative importance between *EMI* and *EDI*. Where *EMI* and *EDI* are considered to be equally important, the effect of fly ash content on *EMDI* is controlled by the greater sensitivity of the *EDI* to the fly ash. Thus, it is shown in this particular case that at later age i.e. when the effect of fly ash is maximal, the highest *EMDI* is found in the SCC with 70% of the cement replaced by fly ash.

Keywords: eco-mechanical-durability index, high volume fly ash, SCC, sorptivity

1. Introduction

In general, durability may be defined as the ability of a product to serve its intended purpose for a period of time (service life) while preserving the minimum required engineering properties without excessive maintenance. The service life of a product is terminated when its engineering properties decrease below the required limits [1].

In terms of concrete, a decrease in the engineering properties over time can be related to deterioration as a result of physical processes, chemical attack, or a combination of both [2, 3]. Chemical attack can



occur when aggressive agents penetrate into concrete. There are many mechanisms by which penetration of aggressive agents into concrete may occur [4, 5]. One of these is the absorption and transmission of liquids, which may contain aggressive agents, into the porous concrete structure by capillary action. The extent to which a material absorbs water in this way can be quantified by its sorptivity.

In concrete, the characteristics of the pores play an important role in determining the rate and amount of absorbed water. The relevant characteristics include the open porosity (inter-connection/network and tortuosity of the pores) and pore size distribution. It is a common perception that concrete with a higher total volume of pores (porosity) will absorb more water. However, one may recognise that concretes with similar porosity can have different sorptivity since pore size, network, and tortuosity are also influential factors. The size of pores in concrete may be classified into three categories: macro pores, capillary pores, and gel pores [6]. Capillary pores induce strong capillary forces that absorb water into the concrete.

Capillary pores are formed when the spaces between cement particles are not occupied by cement hydration products. These pores are usually about 1 μm in diameter. Capillary pores are influenced primarily by the water/cement (w/c) ratio, the degree of cement hydration, and the particle size distribution of the cement. The larger the w/c ratio, the greater the space between the cement particles. The higher the degree of hydration, the more the hydration products will fill these spaces. Consequently, as hydration proceeds, the capillary pores will decrease with time, both in terms of size (pore diameter) and total volume [7]. Meanwhile, the spaces between large particles tend to be wider than the spaces between fine particles. These spaces can be reduced by using particles that have a continuous size distribution. This particle size distribution allows smaller particles to occupy the spaces between larger particles, thus acting as fillers and reducing pore size. Once hydration is complete and the solid phase has formed, what matters is the characteristics of the pores. Discontinuous pores, saturated pores, and narrow-opening pores do not affect the transport properties [8].

Lockington et al [9] developed an analytical method to estimate the water penetration profile into an unsaturated concrete from the sorptivity. The method was developed from the basis of equations describing unsaturated flow through porous media, and is applied to one-dimensional cases of water uptake. Meanwhile, Abyaneh et al [10] proposed a numerical computation to simulate capillary absorption in concrete. The numerical computation was validated by comparing the results with available experimental data in the literature [11] and the analytical method of Lockington et al [9]. In their simulation, aggregate particles are considered as non-sorptive constituents in the hardened cement paste. The main findings of their simulation are as follows: 1) the inclusion of aggregate particles dilutes the volume of porous media (hardened paste) through which absorption can occur; 2) the inclusion of aggregate particles also redirects the water to flow around them, and so increases the tortuosity of the transport path; 3) the amount of water absorbed into the concrete is therefore reduced when there is a higher volume fraction of aggregates; and 4) aggregate size does not significantly affect the rate or amount of absorbed water – while the use of larger aggregates provides additional tortuosity, the effect is negated by the lower number of aggregates, as the volume fraction remains the same. The findings highlight an important conclusion i.e. sorptivity is influenced by the relative volume fraction of the concrete constituents.

The relative volume fraction of self-compacting concrete (SCC) constituents is different to that of conventional concrete. Flowability, filling-ability, and passing-ability are fundamental characteristics of SCC, and can be achieved by maintaining moderate viscosity of the mixture. For this reason, the addition of fine constituents (maximum diameter of 0.125 mm) and the use of superplasticiser are essential. Consequently, in SCC, the volume fraction of fine constituents is higher and that of coarse aggregates is lesser than in conventional concrete [12]. The requirement for a high volume fraction of fine constituents leads to a demand for a higher cement content. Therefore, it is common to obtain a flowable concrete using a relatively high cement content [13]. However, a substantial reduction of cement content can be realised by using cementitious materials such as fly ash to replace the cement. It

is possible to replace a high volume of cement in this way (more than 50% of the total binder). Considering the distinctive composition of SCC as given above, the sorptivity of this concrete is expected to be diverse than that of conventional concrete. Kanellopoulos et al [8] showed that the sorptivity of SCC is lower than that of conventional concrete, and other investigators have corroborated this conclusion [14–16]. However, these findings cannot be explained by the effect of the relative volume aggregate fraction as discussed in the preceding paragraph. Instead, it is suggested that this behaviour could be related to the pore refinement in the hardened paste of SCC. Kanellopoulos et al [8] confirmed that the sorptivity of SCC correlates with the open porosity. The lower the open porosity of SCC, the lower the sorptivity is. The lower open porosity of SCC may be related to a reduction of the open pore volume in the interfacial transition zone (ITZ). The ITZ is influenced by the packing density of the solid ingredients, the w/c ratio, the binder composition, the type of filler, etc. All these parameters are represented in the composition and proportion of the raw materials used for making concrete [17].

The effect of fly ash on the mechanical and durability performance of concrete varies depending on the physical and chemical properties of the fly ash. The variation of fly ash properties obtained from several Indonesian power plants has been identified by Ekaputri et al [18, 19] and Nurwidayati et al [20]. The source of the variation could be traced to the source of coal, mineralogy, coal burning conditions, the method of collecting fly ash, deposit duration, and the sampling period. It should be noted that the coal supplied to the power plants may also vary from time to time, which brings about inconsistent fly ash properties even when taken from the same power plant. For this reason, characterisation of fly ash is necessary before it is used as a cement substitute. With regard to the sorptivity, the use of fly ash to substitute cement can be expected to reduce the sorptivity of SCC, with significant reductions found when the percentage of fly ash is increased up to 50% [21]. It is interesting to know how much further the fly ash percentage can be increased while still reducing the sorptivity. The reduction of sorptivity with the inclusion of fly ash is thought to be due to the filling of micro air voids by finer fly ash particles [21], and also due to the pozzolanic effect of fly ash at a later age [22, 23].

From a sustainability point of view, utilising a high volume of fly ash will bring beneficial effects in terms of reduced carbon dioxide emissions (e-CO₂) and a reduction of unused waste material. Compared to other constituents, cement is the main contributor of e-CO₂ in the production of concrete. The embodied CO₂ (on a mass basis i.e. kg CO₂ per kg of concrete) of cement is about 0.83 [24]. Hence, a partial substitution of cement with fly ash (and other cementitious minerals) becomes a practical way to reduce the e-CO₂. Fly ash itself is a by-product of coal-fired power plants and is considered a waste material. Indonesia has more than 85 coal-fired power plants, which contribute to million tonnes of fly ash every year [25]. If this material is left unused, it eventually becomes an environmental burden.

This research aims to develop an eco-mechanical-durability index that will be used to assess the balance of environment, mechanical and durability performance of SCC containing high volume fly ash. The environment, mechanical and durability performance will be quantified based on the e-CO₂, compressive strength and sorptivity coefficient of the concrete, respectively.

2. Eco-mechanical-durability performance index

The beneficial effects of using fly ash with respect to environmental performance must not compromise the mechanical and durability requirements limit. So, an optimum use of fly ash has to be sought by considering the balance of the environmental, mechanical, and durability performance. The first step to assess this balance is by developing performance indicators capable of measuring the combined three parameters. Fantilli and Chiaia [26] developed eco-mechanical indicators based on eco-mechanical ratios as shown in the following equation:

$$I = \frac{CO_2 \text{ released}}{\text{mechanical properties}} \quad (1)$$

where a lower value of I indicates a better eco-mechanical performance. In a further study by Chiaia et al [27], the inverse of equation (1) is preferred:

$$EMI = \frac{MI}{EI} \quad (2)$$

where EMI , MI , and EI are the eco-mechanical, mechanical, and ecological indices, respectively. In their paper, the numerator and denominator of equation (2) are expressed as $f(MI)$ and $g(EI)$ i.e. correlation function of mechanical index and ecological index, respectively. With equation (2), a higher value of EMI is desirable.

Long et al [28] used an indicator similar to equation (1), but the numerator representing the environmental impact was extended to include the embodied CO_2 (C_I), embodied energy (E_I), and embodied primary resources (R_I). Meanwhile, strength (σ) was adopted as the parameter representing the mechanical properties in the denominator of the equation. Hence, the following set of equations were suggested:

$$C_I = \frac{\text{embodied } CO_2 \text{ (kg}\cdot\text{m}^{-3}\text{)}}{\sigma \text{ (MPa)}} \quad (3.a)$$

$$E_I = \frac{\text{embodied energy (MJ}\cdot\text{m}^{-3}\text{)}}{\sigma \text{ (MPa)}} \quad (3.b)$$

$$R_I = \frac{\text{embodied primary resources (kg}\cdot\text{m}^{-3}\text{)}}{\sigma \text{ (MPa)}} \quad (3.c)$$

In the previous equations, durability has not been considered for assessing the concrete performance. The eco-durability index (EDI) may be calculated using the following equation to account for the contribution of durability:

$$EDI = \frac{DI}{EI} \quad (4)$$

Finally, a combination of EMI and EDI may be expressed into the following equation:

$$EMDI = a\left(\frac{MI}{EI}\right)_n + b\left(\frac{DI}{EI}\right)_n \quad (5)$$

where $EMDI$, MI , DI , and EI are the eco-mechanical-durability index, mechanical index, durability index, and ecological index respectively; a and b are weighting coefficients of MI/EI and DI/EI respectively; and the subscript n indicates that the ratios of MI/EI and DI/EI are normalised to the values of the reference concrete. Hence, equation (5) presents non-dimensional parameters. The weighting coefficient is introduced to account for the relative importance between MI/EI and DI/EI . A higher value indicates that the index is considered relatively more important than the other index. The value of each weighting coefficient is between 0 to 1, and the summation of the two coefficients ($a + b$) must equal 1. The value of these coefficients could vary depending on certain circumstances; for example, if the concrete structure is exposed to a severely aggressive environment, the durability of the concrete holds greater importance, and thus the coefficient b would be greater than a . The assigned values of the coefficients may be determined either by an expert's judgment, the Delphi method, analytical hierarchy process (AHP), or other relevant methods.

3. Experimental investigation

3.1. Materials

The mix proportions of SCCs investigated in this paper are presented in table 1. The maximum aggregate size used in the mixture was 10 mm. The bulk specific gravity (on a saturated surface-dry basis) and the fineness modulus of the coarse aggregates were 2.51 and 6.03, respectively. The corresponding values for the fine aggregates were 2.50 and 2.92. The gradations of both aggregates conformed to the specification of ASTM C-33. The fly ash was supplied from the Cilacap Power Plant and the oxide composition of the fly ash is given in table 2. A modified polycarboxylate based superplasticiser was used in the mixture to aid the formation of flowable concrete. The strengths of the SCCs are presented in figure 1.

Table 1. The mix proportion of SCC with various percentage of fly ash per m³.

ID	Cement (kg)	Fly ash (kg)	CA ^a (kg)	FA ^b (kg)	Water (kg)	Sp ^c (kg)
SCC-50	368.55	368.55	703.2	578.64	211	7.37
SCC-55	331.70	405.41	703.2	578.64	211	7.37
SCC-60	294.84	442.26	703.2	578.64	211	7.37
SCC-65	257.99	479.16	703.2	578.64	211	7.37
SCC-70	221.13	515.97	703.2	578.64	211	7.37

^a Course aggregate

^b Fine aggregate

^c Superplasticiser

Table 2. Oxide composition of fly ash.

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	CaO	MgO	K ₂ O	Na ₂ O	P ₂ O ₅	SO ₃	MnO ₂
45.27	20.07	10.59	0.82	13.32	2.83	1.59	0.98	0.41	1	0.07

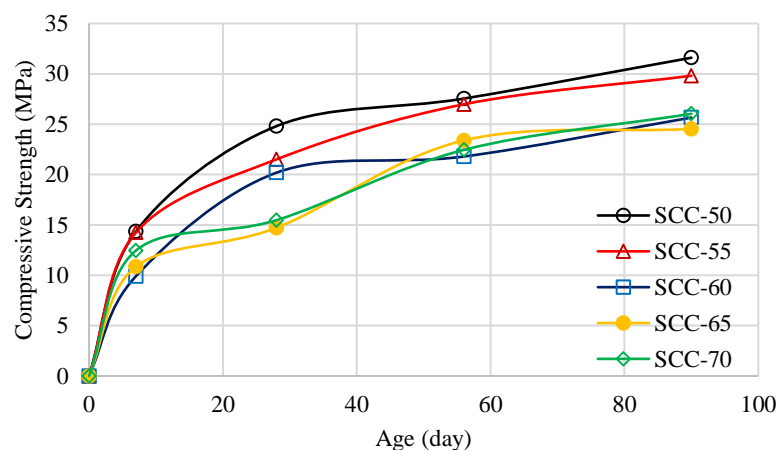


Figure 1. Compressive strength development of SCCs with varying amounts of fly ash.

3.2. Methods

Sorptivity was determined following the method given in ASTM C1858. The method measures the rate of water absorbed through one surface of dry concrete (one-dimensional case of water uptake). The increase of specimen weight over time is measured. The data are then analysed and plotted in

graphical form. The vertical axis of the graph indicates the absorption (I , in mm) where the value is calculated using the following equation:

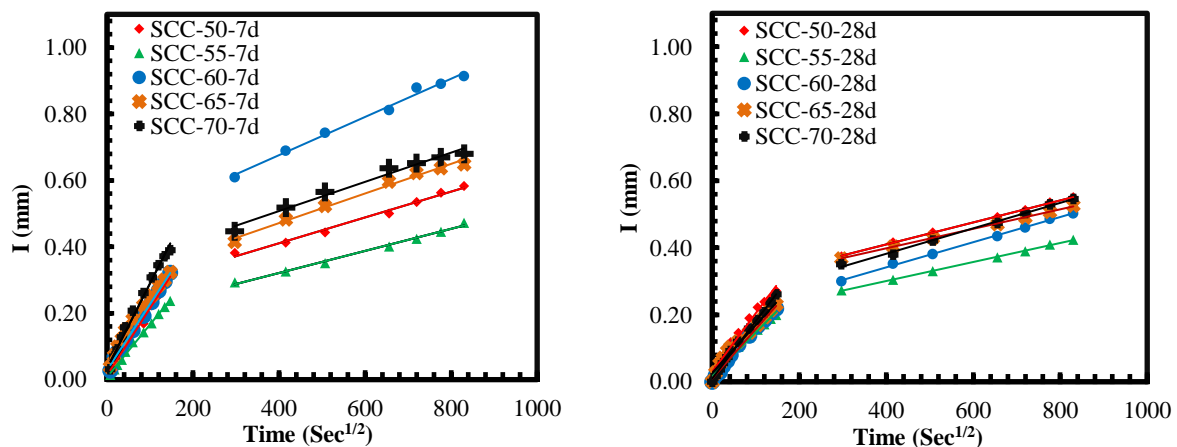
$$I = \frac{m_t}{A \cdot d} \quad (6)$$

where m_t is the change in the mass of the specimen at time t ; A is the exposed surface area of the specimen through which the absorption takes place; and d is the density of water. Meanwhile, the horizontal axis represents the square root of time ($\text{Sec}^{1/2}$). The slope of the graph is determined, to indicate the sorptivity coefficient. In the method given by ASTM C1858, the sorptivity coefficient is separated into two phases: initial and secondary absorption. The initial absorption is determined from the start of the uptake of water until 6 hours, whereas the secondary absorption is determined from 6 hours until 8 days. In this current investigation, the sorptivity of concretes aged for 7, 28, 56, and 90 days were measured. The obtained sorptivity coefficients were calculated as average values from 5 measurements. Hence, a total of 100 specimens were prepared for this investigation.

4. Results and discussion

4.1. Sorptivity

The cumulative amount of absorbed water over time is presented in figure 2. The profiles of cumulative absorbed water by all SCCs reveal two distinctive rates of water absorption. At the start of the absorption process, a fast rate of water absorption can be identified as shown by the initially steep slope of the lines in figure 1. After 1 day (about $294 \text{ Sec}^{1/2}$), a clear change of the slopes can be observed. The slope of the lines decrease, corresponding to the slower rate of water absorptions at longer times, as the pores within the concrete are already partially saturated. In the method given by ASTM C1858, the initial and secondary slopes represent the values of the initial and secondary sorptivity coefficients, respectively.



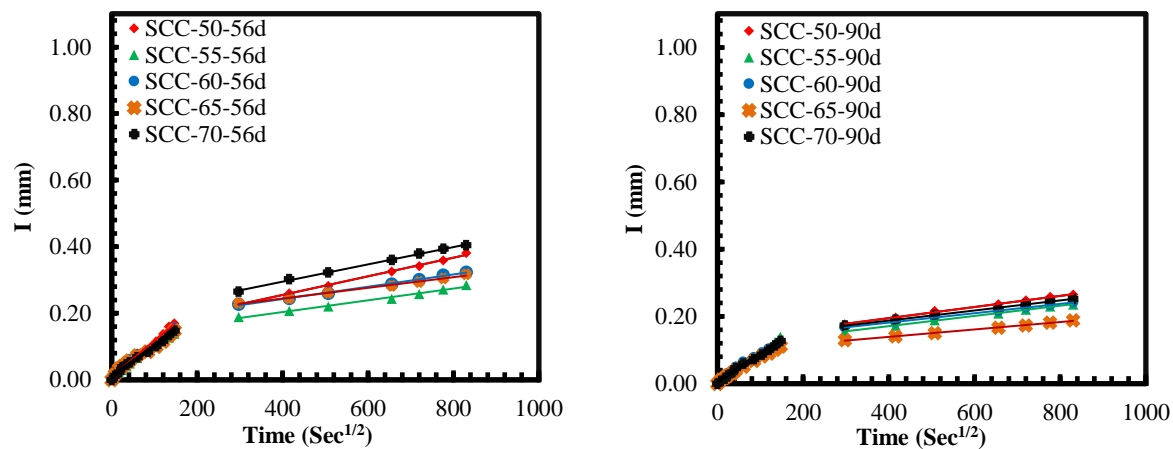


Figure 2. Absorption of water into SCCs at various ages (7, 28, 56 and 90 d).

The data of initial absorption presented in figure 2 are too crowded, making it difficult to compare between mixtures. However, a least square linear regression analysis has been performed for each set of absorption data mixture to study the effect of concrete age and fly ash content on the sorptivity coefficients. The results of the analysis are presented in figure 3. It is noticeable that both the initial and secondary sorptivity coefficients decrease with concrete age. The initial sorptivity coefficients of SCCs at 28 days are reduced by 18–34% compared to those at 7 days. The corresponding reduction of secondary sorptivity coefficients is 13–35%. Further decreases of both the initial and secondary sorptivity coefficients can be expected at later ages. At 90 days of age, the initial sorptivity coefficients are reduced by 59–68% compared to those at 7 days. For the secondary sorptivity, the reduction is counted at 54–76%. The reduction may be related to a change in the pores' structure as a result of the progressing hydration. When the concrete first hardens, a network of capillary pores is formed, through which water can easily be absorbed. As hydration progresses, these capillary pores are gradually occupied by cement hydration products, which disrupt the connectivity between these capillary pores. In addition, at later ages, a sufficient pozzolanic reaction between the fly ash and hydrated lime takes place, bringing a similar effect. This finding matches those observed in other literatures [22, 23].

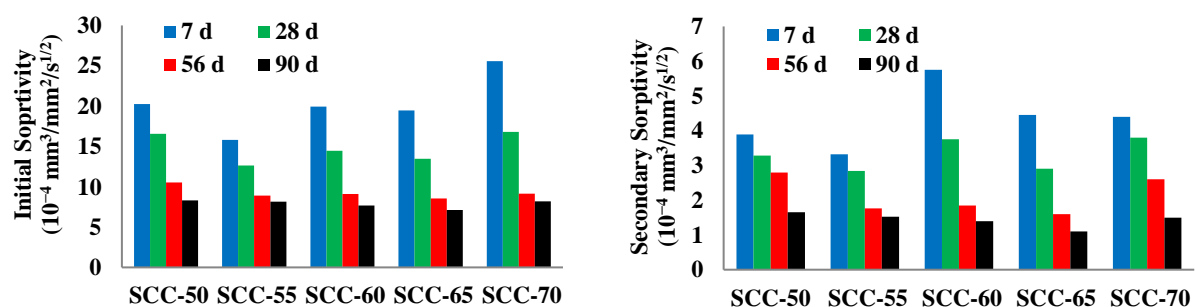


Figure 3. Initial and secondary sorptivity coefficients of SCCs at various ages.

The sorptivity coefficients are also affected by the amount of cement replaced with fly ash. At an early age (7 d), the lowest values of both the initial and secondary sorptivity coefficients occur at a 55% replacement level. At a later age (90 d), the lowest values are shifted to the 65% replacement level. The highest initial sorptivity was observed for the 7-day SCC with the 70% replacement level. The processes, mechanisms, and reactions that contribute to this change in sorptivity with both the amount of fly ash and time are explained as follows.

The capillary pores are formed when empty spaces between the solid particles are not occupied by the hydration products. Fly ash, with its finer particle size, can refine these spaces before hydration takes place; hence, replacing cement with fly ash is expected to reduce the pores. However, the replacement level reaches an optimum value when the lowest packing density of the mixture is achieved. For the concrete investigated in this study, this optimum value is found at a 55% replacement level. Meanwhile, at 7 d of age, the cement hydration is still progressing as indicated by the strength development in figure 1. The strength of SCC at 7 d only represents about 39–48% of the strength at 90 days. Thus, the hydration products have not fully occupied the inter particle spaces and so, the original packing density of the mixture becomes a crucial factor in determining the pore characteristics at early age. When the replacement level is too high (70%), fly ash tends to dilute the cement particles. Consequently, less hydration products are available to occupy the inter particles spaces. On the other hand, at a later age (90 d), the hydration is nearly completed and sufficient pozzolanic reaction has also taken place. The capillary pores that were formed at an early age are now occupied by the hydration and pozzolanic reaction products. The replenishment of empty capillary pores with hydration and pozzolanic reaction products at a later age is a significant factor in determining the pore characteristics. All of the processes (formation of capillary pores that occupy inter particles spaces, refinement of capillary pores in the progress of hydration, and replenishment of empty capillary pores with hydration and pozzolanic products) requires balanced quantities of cement and fly ash to achieve an optimal value of sorptivity. This study indicates that a 65% replacement level of cement with fly ash gives the lowest value of both initial and secondary sorptivity coefficients at 90 d.

4.2. *Eco-mechanical-durability performance*

Implementation of equation (5) for assessing the eco-mechanical-durability performance of concrete requires consideration in assigning relevant parameters to be used as indicators of eco, mechanical, and durability performance:

With respect to ecological performance, the following parameters may be considered to evaluate environmental impacts related to the production, use, maintenance, and demolition of concrete; environmental emissions, energy consumption, and resource depletion. Emission of carbon dioxide (e-CO₂) from concrete production and transportation is estimated to be responsible for approximately 10% of the total man-made CO₂ in the atmosphere [28]. Therefore, e-CO₂ becomes the most significant parameter to assess the environmental impact of concrete. Purnell and Black [24] and Long et al [28] reviewed embodied CO₂ values for major concrete constituents; cement itself accounts for about 0.83 kg CO₂ per kg of concrete. Other embodied CO₂ values for major concrete constituents have been summarised in [28] and these values are applied for this study.

In previous studies [26–28], the mechanical performance of concrete is represented by either strength or a combination of strength and ductility. Compressive strength (σ) has been chosen for this evaluation since this is the fundamental property required in the utilisation of concrete as structural elements.

There are several indicators that can be considered suitable for the purpose of assessing the durability performance of concrete, such as permeability, sorptivity, bulk resistivity, chloride diffusion, and abrasion resistance [8, 22, 23, 29, 30]. All or part of these parameters may be employed to comprehensively evaluate the durability performance of concrete. For the current study, it is simply sorptivity that is adopted as the indicator. Hence, for the SSCs evaluated in this investigation, the durability performance is only relevant to concrete that is in contact with water. It is noted that a more durable concrete would have a lower sorptivity coefficient i.e. durability index (*DI*) is inverse of the sorptivity coefficient.

Given the above considerations, equation (5) is now transformed as follows:

$$EMDI = a\left(\frac{\sigma}{\text{embodied } CO_2}\right)_n + b\left(\frac{s^{-1}}{\text{embodied } CO_2}\right)_n \quad (7)$$

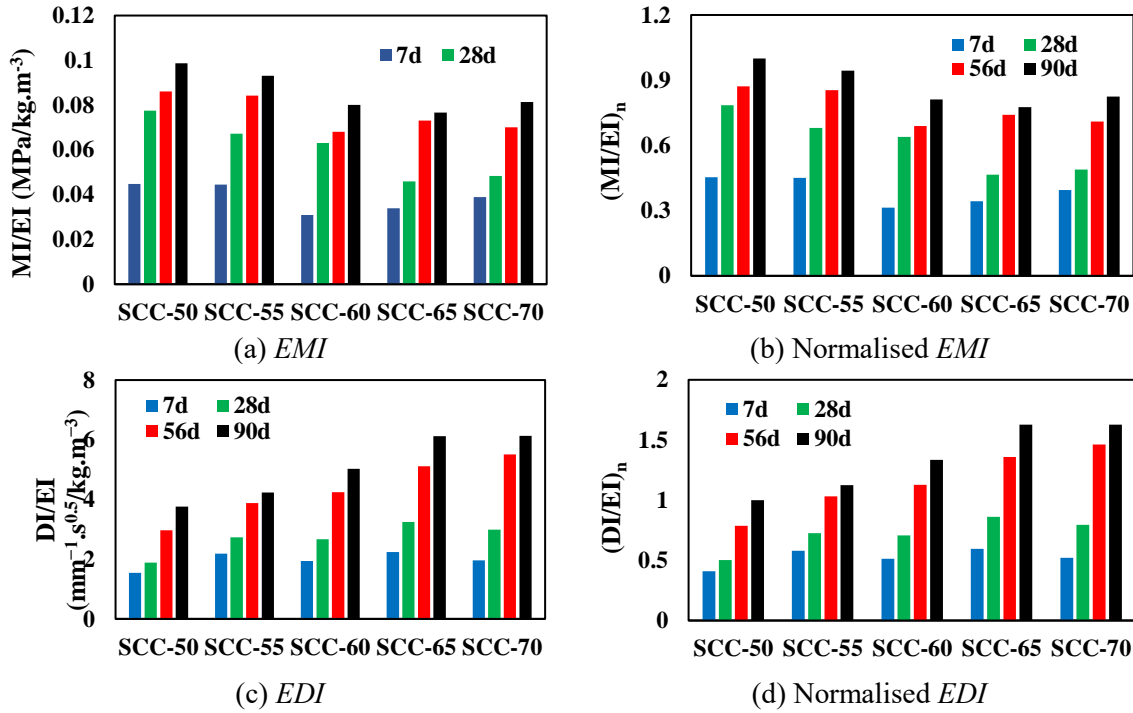


Figure 4. Eco-mechanical index (EMI) and eco-durability index (EDI) with their respective normalised values

The eco-mechanical index ($EMI=DI/EI$) and the eco-durability index ($EDI=DI/EI$), along with their normalised values, are given in figure 4. The normalised values are defined as the ratio of the EMI and EDI of each SCC to the corresponding values of SCC-50 at 90 d. Thus, the values for the reference concrete (SCC-50 at 90 d) must be 1, and index values less than 1 indicate that the performance of the concrete is lower than this reference concrete, and vice versa. The later age (90 d) of concrete was chosen as a reference since at this age the effect of fly ash is maximal. The EMI is expressed in MPa/kg.m⁻³ while EDI is expressed in mm⁻¹.s^{0.5}/kg.m⁻³. The denominators represent the kg of embodied CO₂ per m³ of SCC; the compressive strength used to calculate the EMI is specified in MPa; and an inverse unit of sorptivity is used for determining EDI i.e. mm⁻¹.s^{0.5}. It is clear from figure 4 that the beneficial effects of fly ash increase as the concrete ages; both the EMI and EDI rise with time. Figure 4 also shows that SCC-50 gives the highest value of the EMI . Increasing the replacement level of cement with fly ash above 50% tends to decrease the EMI . On the other hand, the trend is reversed with respect to the EDI . An increase of fly ash content will result in an increase of the EDI .

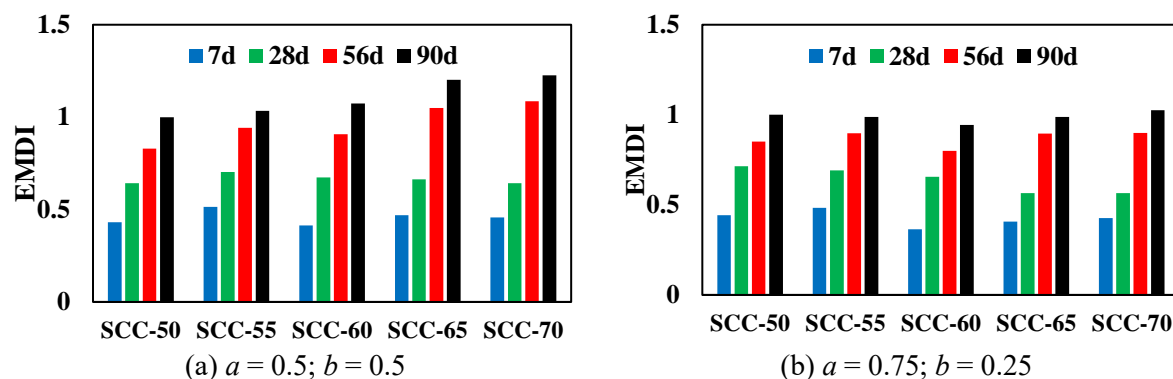


Figure 5. The eco-mechanical-durability index (EMDI).

The combined value of *EMI* and *EDI* i.e. *EMDI*, calculated using equation (7) with the normalised values, is presented in figure 5 for two cases. In the first case, both the *EMI* and *EDI* are considered to be equal factors. Hence, the assigned values of a and b in equation (7) are both 0.5. Figure 5.a shows that at a later age (90 d) i.e. when the beneficial effect of fly ash is maximised, the highest *EMDI* is found for SCC-70. A reduction of *EMI* with an increase of fly ash is counter balanced by the increase of *EDI*. Since the *EDI* is more sensitive to changes to the fly ash content than the *EMI*, the result is that the *EMDI* increases with increasing fly ash content. For the second case, where the *EMI* is considered to be relatively more important than the *EDI* by assigning values of $a = 0.75$ and $b = 0.25$, an increase of fly ash content does not significantly affect the *EMDI* of SCCs at 90 days (see figure 5.b).

The preceding paragraph illustrates the use of *EMDI* as a means to assess the eco-mechanical-durability performance of SCCs incorporating various amounts of fly contents. The *EMDI* is especially useful when the effects of fly ash on the mechanical and durability indicators are not aligned. The *EMDI* can serve in seeking the best composition of a particular concrete mixture in a specific case.

5. Conclusions

The main conclusions of this study are summarised as follows:

- The sorptivity of SCCs incorporating various high-volume fly ash contents decreases with time. At 90 days of age, the initial and secondary sorptivity coefficients are reduced by 59–68% and 54–76% respectively, compared to those at 7 days.
- At an early age (7 days), the lowest value of both the initial and secondary sorptivity coefficients occur when 55% of cement is replaced with fly ash. However at a later age (90 days), the lowest values are shifted to the 65% replacement level.
- An increase in fly ash content tends to decrease the eco-mechanical index (*EMI*) but increase the eco-durability index (*EDI*) of SSC.
- Given the same weighting factor of *EMI* and *EDI*, the highest eco-mechanical-durability index (*EMDI*) is found for the SCC where 70% of cement is replaced with fly ash.

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