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Multiscale assessment of asphalt emulsion as a toughening modifier for self-compacting concrete: mechanical behaviour, microstructural analysis, and RSM-based modelling

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ABSTRACT

The development of self-compacting concrete (SCC) has revolutionized modern infrastructure by facilitating the construction of high-strength and intricate structures such as rigid pavements, bridges, tunnels, and skyscrapers since it has superior flowability and capacity for self-consolidation without external vibration. Despite all these advantages, the inherent brittleness and poor energy absorption capacity are significant shortcomings when it is subjected to impact and dynamic loading. The purpose of this investigation is to identify and ascertain the performance of an asphalt emulsion (AE) as a toughening agent on SCC to increase its energy absorption capability without significantly affecting its mechanical properties and fresh characteristics. For this study, five mixes were cast, including a reference mix and four SCC mixes containing 5, 10, 15, and 20% AE content (by weight of cementitious material). Fresh properties were measured using slump flow and J-ring tests, while hardened concrete properties included mechanical behaviour (stress-strain curve, toughness index), microstructure analysis (pore size distribution, XRD), and response surface methodology (RSM)-based modelling. This study shows that AE effectively enhances the postpeak deformation behaviour and the energy dissipation of SCC at the cost of a small reduction in compressive strength. The toughness index of the mixture with 5%, 10%, 15%, and 20% AE was improved by 5.21%, 17.00%, 24.13%, and 39.52% compared with the control, indicating an enhanced ductility and toughness with increasing AE content. In addition, the fresh properties were all within the permissible limits for SCC mixtures, suggesting that the workability of SCC was not negatively influenced by the addition of AE. Two very reliable models for predicting the slump flow, compressive strength, and flexural strength were obtained based on the RSM analysis and demonstrated a strong correlation between laboratory and predicted values. The optimum amount of AE based on both the fresh and hardened state performance of the concrete should be 10%. In addition, a suitable dosage of 10% AE can contribute to a compromise of improved toughness and energy dissipation, sufficient mechanical performance, and workability. The results suggest that AE is a promising, eco-friendly, and low-cost admixture for enhancing the toughness and impact resistance of concrete for durable and resilient transportation and civil infrastructure.

1 Introduction

Concrete is the most common construction material in the world, with a high amount of annual production due to its ease of handling, durability, availability, and economic value [1-3]. In transportation infrastructure, concrete is the material of choice for the majority of rigid and semirigid pavements, railway tracks, and bridges, as well as other high-loaded civil

engineering structures [4, 5]. Long-term performance in these structures relies heavily on the mechanical behaviour of concrete [3, 6]. However, it has always been known that normal concrete is intrinsically quasibrittle with relatively low tensile strength, fracture toughness, and impact energy absorption capacity [3, 6]. These limitations may lead to premature crack initiation and propagation caused by traffic load, impact, and thermal cycling or cyclic fatigue and thus

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reduce serviceability and durability [7, 8]. Improving the toughness and deformability of concrete without damaging the structural performance is an important issue in the next generation of high-performance concrete [9, 10]. SCC has emerged as an attractive alternative to conventional concrete due to its excellent workability, and its use in pavement construction can enhance paving efficiency, reduce project costs, and improve the durability of pavement structures [11–13]. For example, the filling layer in the China Railway Track System (CRTS) III slab track is constructed using SCC, and the SCC filling layer in the CRTS III ballastless slab track plays the role of load transfer, geometrical adjustment, position control, attenuating vibration generated by moving trains and providing support to the track structure [14, 15]. It is subjected to dynamic loads during train operation, and its mechanical properties are affected by the loading time and frequency. Thus, the filling layer SCC must possess adequate strength and energy absorption capacity to meet functional requirements [16, 17]. However, despite the improved properties of SCC compared to conventional concrete, it remains associated with brittleness and inadequate toughness, thereby limiting its widespread use in construction projects [13, 16]. To enhance the energy absorption capacity of concrete, researchers have incorporated various materials, and significant progress has been achieved [17, 18]. Studies on the use of rubber aggregate (RA) in SCC have shown that RA causes a decrease in the strength of SCC but significantly improves the damping performance [19, 20]. Fibres are also regarded as good materials for improving the energy absorption of concrete, and studies have shown that at the same loading rate, fibre-reinforced concrete absorbs more impact energy than normal concrete [21, 22]. Although the use of energy-absorption materials such as fibre and RA significantly enhanced the energy-absorption capacity of concrete-like materials, it also reduced workability. SCC is widely used for its excellent workability [18, 23]; thus, there is a need for an alternative material that can improve the energy absorption property of SCC without compromising its workability [23, 24].

Therefore, some researchers consider the employment of polymers to enhance the mechanical properties of SCC and describe that SCC with enhanced strength, low dynamic elastic modulus, and improved durability could be formed through the integration of polymers [25, 26]. SCC with improved performance properties can be achieved by incorporating polymers, but the cost increases accordingly. That is, polymers could excellently modify the properties of SCC, but they were costly. Therefore, a more economical material is needed for this purpose. Some previous studies have suggested that asphalt is a good material for the required properties of SCC [24, 27]. In addition, asphalt emulsion (AE) is less expensive, and because of its flexible nature, it can effectively enhance the toughness and durability of SCC [11]. Previous studies on the use of AE in cement-based materials have indicated that at the same loading rate, cement asphalt emulsion mortar (CA mortar) is more sensitive to strain rate than concrete [28, 29]. Zhang *et al* [30] reported that an appropriate dosage of AE enhanced the durability of SCC without adversely affecting its workability. Li *et al* [27] investigated the dynamic mechanical properties of SCC designed to incorporate asphalt-coated coarse aggregate (ACCA) and found that the incorporation of ACCA greatly enhanced the impact resistance and impact toughness index of SCC. However, the impact toughness index largely depends on the thickness of the asphalt layer on the aggregate surface. Additionally, previous studies

indicated that recycled asphalt pavement (RAP) can be employed to produce SCC with appropriate workability and improved permeability properties [31–33]. Although SCC with appropriate properties has been produced by incorporating RAP and ACCA, the literature on the use of AE in SCC and its effects on both fresh and hardened properties remains very limited. Because AE is liquid at room temperature, it can be easily incorporated into concrete; thus, integrating AE into SCC might be cost-effective and less challenging than using RAP and ACCA.

In the pursuit of optimizing complex systems and processes, scholars and engineers often encounter numerous variables that influence the desired outcome. Response surface methodology (RSM) has been a powerful and systematic approach to tackle this challenge, enabling researchers to explore the intricate relationships between input variables and the response of interest [34, 35]. RSM is a collection of statistical and mathematical techniques used to model and analyse the relationship between a set of independent variables and the output response of a system. It is commonly used in scientific research, engineering, and manufacturing to improve and optimize the performance of complex systems [34, 36, 37]. It operates on the premise that a suitable mathematical model can be developed to represent the underlying relationships by systematically varying the input variables and observing the corresponding responses. This model, often expressed as a response surface, can be employed to optimize the system, predict outcomes, and guide decision-making [35, 38]. The versatility of RSM enables researchers to optimize processes, design experiments, and gain deeper insights into complex systems [39, 40].

RSM stands out as an incredibly effective approach due to its economical use of partial factorial designs, such as star designs or CCD. Consequently, minimal experimental data points are required [41, 42]. Among the prevalent first-order designs in RSM are the Plackett–Burman, simplex designs, and 2k factorial, while the Optimal (custom) design, Definitive Screen (DSD), Box–Behnken, and Central Composite are the typical examples of widely used second-order designs [39, 43]. For this study, AE was integrated into the SCC; the workability, quasistatic compressive strength, and pore structure were studied. The compressive stress–strain curves were discussed, and the toughness index of SCC with AE was evaluated. The pore structure of the SCC with AE was studied using microscopy image analysis. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) tests were also performed to discuss the effects of AE on the microstructural development of SCC. This research work provides both theoretical and technical guidance on using AE to improve the performance of SCC.

2 Materials and methods

2.1 Materials

Ordinary Portland cement (OPC), P.O 42.5 (C), which complies with the Chinese specification GB175-2007 [44], was adopted as the binder. Other cementitious materials, such as fly ash (FA), ground granulated blast furnace slag (GGBS, named SL), viscosity-modifying agent (VMA), and expansion agent (EA), were blended into the binder to improve the rheological and mechanical performance of the self-compacting concrete (SCC). Thus, the cementitious binder materials used in this study comprise cement (C), FA, SL, VMA and EA. The physical characteristics and chemical composition (oxide) of the cementitious materials, as

measured by X-ray fluorescence (XRF), are shown in Table 1. Crushed gravel (G) with a maximum nominal size of 5-20 mm and apparent density of 2680 kg/m³ was adopted as the coarse aggregate, whereas the fine aggregate was natural river sand (S) with an apparent density of 2650 kg/m³, fineness modulus of 2.6, and maximum particle size of 4.75 mm. The grading and quality specifications for the aggregates for the production of SCC were also met. A cationic asphalt emulsion (AE) with 60% residual asphalt was utilized as the modifier for improving the toughness and energy absorption capability of SCC. The main physical characteristics of the AE are presented in Table 2. A polycarboxylate-based superplasticizer (SP) with a water-reducing ability of approximately 26% was utilized to obtain the desired workability while guaranteeing the mixture stability. The mixing water (W) of all concrete mixtures was potable tap water. To decrease the entrapment of air induced by the mixing of asphalt emulsion and guarantee a homogeneous microstructure in the ITZ and concrete mixture, silicone-type defoamer (D) was also added to the mixtures at a dosage of 0.1% with respect to the total mass of cementitious materials. The choice of these materials ensured the feasibility of the fabrication of SCC with good fresh status stability and provided an adequate framework

for thoroughly analysing the effect of AE on the mechanical behaviors, toughness, and microstructure of hardened concrete.

2.2 Mix proportion

Five different self-compacting concrete (SCC) mixes were formulated to investigate, in a systematic way, the effect of asphalt emulsion (AE) addition on the fresh, mechanical, and microstructural characteristics of SCC. An experimental plan consisted of one mix without AE as a reference (SC0) and four mixes containing 5%, 10%, 15%, and 20% AE (SC5, SC10, SC15, and SC20), respectively. AE was used as a percentage of the total amount of cementitious materials. Other mix materials, proportions of constituents (aggregate grading and binder composition), as well as the water/binder (w/b) ratio, were kept the same for all the mixes to avoid other factors influencing the mixes' performance instead of AE. The w/b ratio of 0.34 was selected because it allows suitable workability conditions as well as an equivalent level of hydration of SCC mixes, thus being able to cover SCC requirements for workability. The mix proportion details of the five SCC mixtures are given in Table 3.

Table 1. Physical and chemical properties of cementitious powder materials

Oxides	Materials			
	C	FA	SL	EA
SiO ₂	19.86	55.70	26.10	6.00
Al ₂ O ₃	4.81	28.39	13.80	3.26
Fe ₂ O ₃	4.67	4.69	14.10	0.94
CaO	59.48	3.42	33.60	60.85
MgO	2.78	0.75	8.10	2.83
SO ₃	2.68	0.88	-	24.21
eq-Na ₂ O	0.65	0.95	0.45	0.80
Loss on ignition	2.40	4.70	2.10	6.60
Specific surface area (m ² /kg)	332	450	420	320

Table 2. Properties of Cationic Asphalt Emulsion

Parameter	Unit	Value
Penetration (25 °C, 100 g)	0.1 mm	82
Storage stability (1d, 250 °C)	%	0.35
Polarity	-	Cationic
Ductility (15 °C)	cm	52
Solubility (trichloroethylene)	%	97.2
Residue on screen (1.18 mm)	%	0.02
Solid content	%	60

Table 3. SCC mix proportions with AE (kg/m³).

Mix ID	C	FA	SL	EA	VMA	W	SP	S	G	AE	D
SC0	302	62.5	62.5	42	31	170	10.5	835	834	0	0
SC5	302	62.5	62.5	42	31	160	10.5	835	834	25	0.5
SC10	302	62.5	62.5	42	31	150	10.5	835	834	50	0.5
SC15	302	62.5	62.5	42	31	140	10.5	835	834	75	0.5
SC20	302	62.5	62.5	42	31	130	10.5	835	834	100	0.5

C: cement; FA: fly ash; SL: slag; EA: expansion agent; VMA: viscosity-modifying admixture; W: water; SP: superplasticizer; S: sand; G: gravel; AE: asphalt emulsion; D: defoamer.

2.3 Sample preparation

The SCC mixtures were prepared using a 60 L pan concrete mixer in a standard mixing procedure to maintain an even distribution of the asphalt emulsion (AE) in the mixtures and to guarantee the uniformity of the whole batch. The mixing process started with blending the dry materials: cementitious constituents, coarse and fine aggregates, for 30 s at a speed of 50 rpm to reach a homogeneous dispersion of the materials. Next, the predetermined amount of mixing water was added gradually while mixing was maintained. Afterwards, the asphalt emulsion defoaming agent (AE-D) solution, premixed in an appropriate amount, was slowly added and mixed for approximately 2 min to obtain the total dispersion of AE in the cementitious mixture. Finally, the prescribed content of the polycarboxylate-based superplasticizer (SP) was added to reach a certain degree of self-compactability. The measured fresh properties of the SCC mixtures: slump flow and J-ring test performed just after mixing in accordance with the SCC tests are given in Table 4. The whole testing was conducted in controlled laboratory conditions at ambient temperature between 20–25°C. Once the fresh-state testing was complete, the SCC mixtures were poured into moulds of suitable dimensions to facilitate each mechanical and microstructural test needed. Entrapped air was expelled without disturbing the self-compacting ability of the concrete by gentle tapping of the moulds where required (without external vibration). The moulds were covered to minimize moisture loss, then demoulded after 24 h and placed in a standard curing chamber to be cured at 20±2°C and 95–100% relative humidity until the respective testing ages.

2.4 Experimental methods

2.4.1 Workability properties test

In the fresh state, slump flow and J-ring tests were performed to assess the flowability and passing ability of the

self-compacting concrete (SCC) mixes, respectively [45]. In the slump flow test, fresh SCC was introduced into a slump cone, and the overflow was levelled with the slump cone and pulled up. Then, two average mutually orthogonal slump spread values were registered (SF), along with the time taken to reach a spread of 500 mm (T) as a measure of viscosity (Fig. 1a). In the J-ring test, a J-ring was placed at the center of the slump cone while casting fresh SCC, simulating reinforcement bar congestion. Once the concrete had stopped spreading, the average of two mutually orthogonal slump spreads was measured (JF) (Fig. 1b). The difference between the SF and JF also indicates the passing ability of SCC, and the lower the value is, the higher the passing ability of concrete to overcome obstacles without getting stopped. This test programme will ensure adequate comparison of the fresh concrete and self-consolidating behaviour of the SCC mixture with variations in asphalt emulsion content.

2.4.2 Quasistatic compressive test

A compressive property test was carried out after 56 days of curing using a servo-hydraulic testing machine (Instron 1342) under quasistatic uniaxial compressive loading according to the Chinese Standard GB/T 50081-2002 [46]. Figure 2 shows the experimental setup and cylindrical samples (Φ75 mm × 75 mm). The test was performed in displacement control at a rate of 0.15 mm/min, approximately 3.0 10 s. To avoid interface friction, petroleum jelly was spread on specimen surfaces. An extensometer was used to record the longitudinal displacement. Three replicates were performed and averaged for each mix. Based on the stress–strain curve results, the compressive behavior and energy absorption ability of the AE-modified SCC mixture were assessed. Energy absorption capability, termed toughness, can be calculated as the area under the stress–strain curves [47–49]. As the indicator for direct quantitative analysis of total toughness, the toughness index (T) suggested by Khaloo *et al.* [50] was selected, as shown in Fig. 3. The

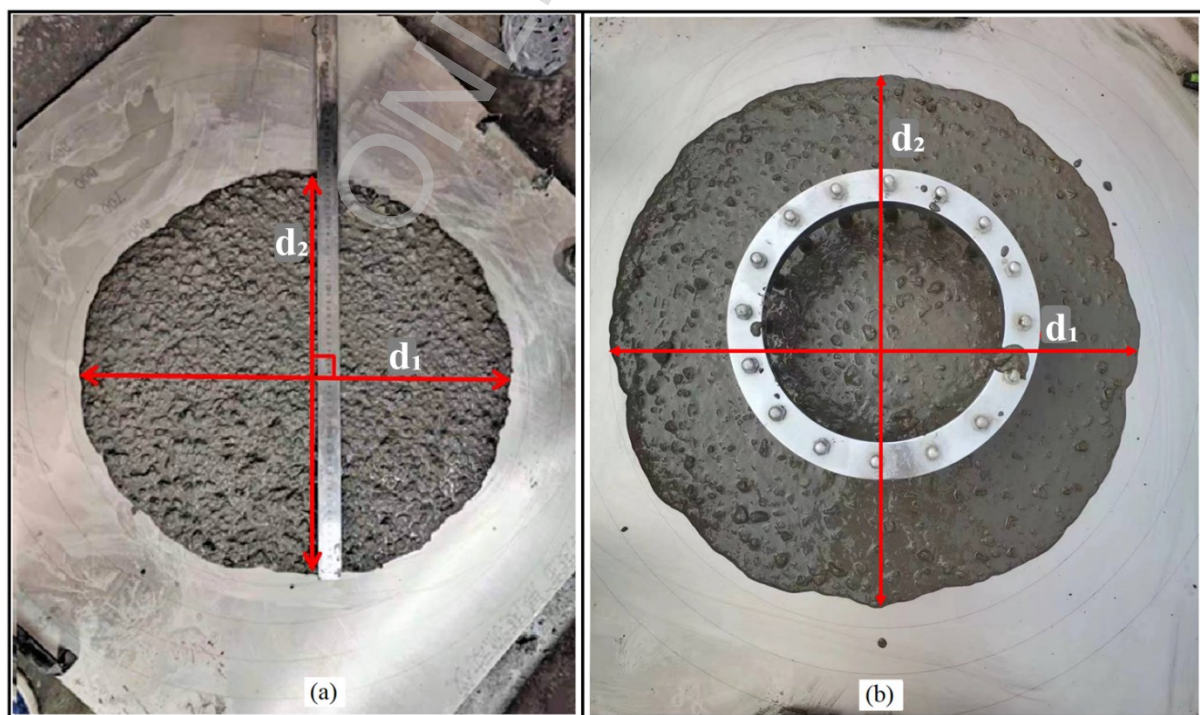


Figure 1. Workability of SCC: (a) slump flow; (b) J-ring flow

equation for calculating the toughness index T is shown in Equation (1). The toughness index T integrates the combined effects of compressive strength and deformability into one value.

$$T_i = \frac{T_{80}}{T_{100}} \quad (1)$$

where T_{80} represents the region under the stress–strain curve up to 80% of the maximum stress (illustrated by the sum of S_A and S_B in Fig. 3); and T_{100} is the region under the stress–strain curve up to the highest stress (illustrated by S_A in Fig. 3).

2.4.3 Pore structure test

The pore structure of the hardened concrete specimens was studied via the pore structure analyser CABR-457, designed and manufactured by the China Academy of

Building Research, as shown in Fig. 4. After 56 days of standard curing, a slice piece of concrete with dimensions of 100 mm × 100 mm × 20 mm was cut from the concrete cube specimen (100 mm × 100 mm × 100 mm) for this test. A clean, smooth surface was selected for the image observation, and it was polished again with a grinding machine to enhance its smoothness and clarity, ensuring optimal conditions for observation. After grinding, an ultrasonic cleaner was used to clean the polished test blocks, which were then oven-dried at approximately 55°C. After drying, the observation surface was highlighted with a marker, and the drying process continued for a few minutes. Subsequently, the specimens were removed from the oven, and the observation surface was coated with a heated mixture of zinc oxide and Vaseline, ensuring that the white paste (a mixture of zinc oxide and Vaseline) effectively filled all the pores on the observation surface. Excess paste was scraped off after cooling to room temperature. The test

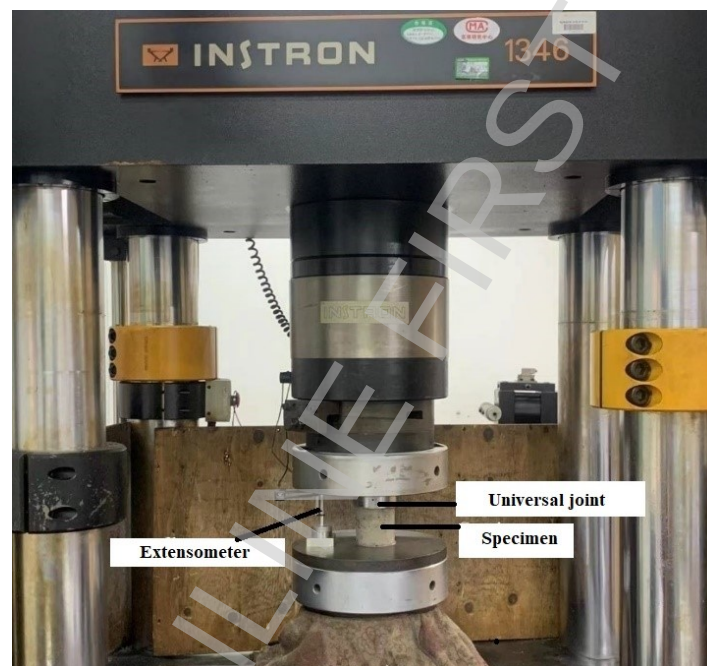


Figure 2. Quasistatic compression test

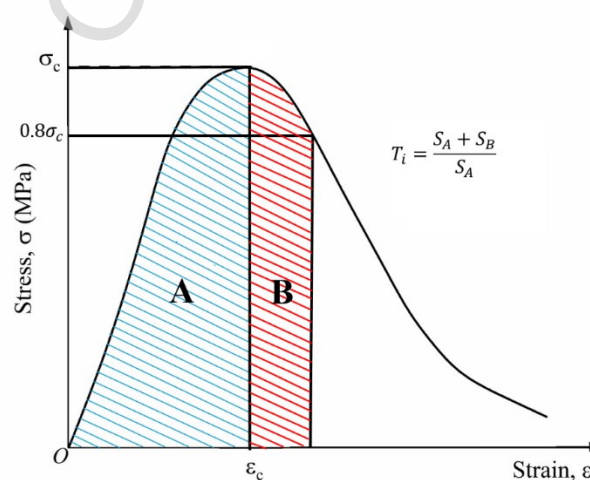


Figure 3. Definition of toughness index

specimen was then put on the stage and observed using a pore structure analyser, with the observation surface exposed to the microscopic camera. Before the observation started, the camera focus was adjusted to obtain a clear image of the test surface. During the observation, the white pixels in the image were identified by the computer as pores. Initiating from the upper left corner of the specimen, the observation surface was scanned five times along the X and Y axes, and from the images captured by the computer, the pore size distribution and porosity could be computed automatically using a C++ software design language based on the following equations [51]:

$$A_i = \sum_{j=1}^{m_i} A_j \quad (2)$$

$$D_j = \sqrt{\frac{4A_j}{\pi}} \quad (3)$$

$$A\% = \frac{\sum_{i=1}^{250} A_i}{250A_T} \quad (4)$$

where A_i = total pore area (cm^2) observed in the i th microscopy images A_j = area of the j th pore (cm^2) D_j = equivalent diameter of the j th pore (cm^2) A_T = total analysed area (cm^2) of each microscopy image. $A\%$ = total pore area ratio (%) of the sample. Three regions were subjectively chosen from each sample, and average results were considered to guarantee statistical stability.

2.5 Response surface methodology-based modelling

RSM software (i.e., Design-Expert 13) was used in this study to analyse experimental data using the optimal (custom) method, enabling statistical analysis and model development to predict the effects of AE and curing period on the properties of self-compacting concrete. For the purpose of model development, the compressive strength test was conducted at different curing periods; three cubes ($100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$) were tested from each group, following Chinese standard GB/T 50081-2002 [46], the average of the three results was recorded. The experimental results from the compressive strength tested at different curing periods and that of workability test was then used as input parameters. The regression model for the optimal calculation of the input parameter in this study is given by Eq. (5).

$$y = \beta_0 + \sum_{i=1}^n \beta_i X_i + \sum_{i=1}^n \beta_{ii} X_i^2 + \sum_{i < j} \beta_{ij} X_i X_j + \epsilon \quad (5)$$

where y is the response, β_0 is the intercept, β_i and β_{ii} are the first- and second-order coefficients, β_{ij} is the interaction coefficient, X_i and X_j represent the independent variables, and n and ϵ represent the number of variables and the model's error, respectively [52].

3 Results and discussion

3.1 Flowability

Table 4 shows the fresh properties of SCC mixtures incorporated with different amounts of asphalt emulsion (AE). In general, as AE increased, the flowability and passing ability of SCC decreased, while the passing performance worsened with increased AE content. As seen in Table 4, slump flow values decreased as the amount of AE increased. This decrease in slump flow is due to the lower amount of free water, since part of the total water used in the mixtures was provided by asphalt emulsion, as shown in Table 3; free water for lubrication in the SCC mixes decreased. Additionally, AE can hinder cement hydration and the increase in fresh matrix viscosity that causes cement paste, as well as aggregate movement [30, 53]. With a reduction in flowability for SCC with 5 and 10% AE relative to the control mix, a greater flow loss occurred for specimens prepared with 15 and 20% AE. T_{50} flow values increased with increasing AE content, as shown in Table 4, from 6.7 s (SC0) to 10.5 s (SC20), which is in line with the observed trend of decreased flowability. The maximum T_{50} value was obtained in SC20, which meant that the AE content significantly increased the viscosity of SCC and delayed its flow due to self-weight. Additionally, the difference between the SF and JF values increases with the AE dosage, which proves that the mixture has a gradual decrease in the passing ability when the dosage is increased. This trend becomes remarkable in the 15% and 20% AE mixtures and indicates high flow restrictions within a reinforcement model and a strong possibility of blocking the concrete. However, the results are in accordance with the requirements of passing ability in ASTM C1621 [54], and the introduction of AE to the fresh concrete mix with AE dosage up to 10% does not compromise the self-compacting behaviour of concrete.

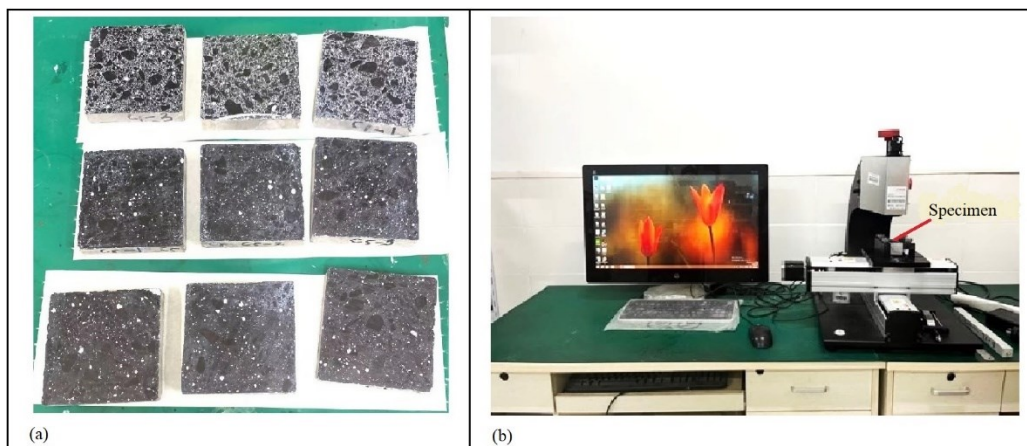


Figure 4. Pore structure test: (a) prepared specimens; (b) pore structure analyser

From the above analysis, we found that asphalt emulsion can enhance the fresh concrete viscosity and moderately affect the workability of the concrete mixtures. Workability in mixes with 10% AE is still acceptable, with the benefits of mixture stability compared to higher AE percentages. The addition of more AE content would affect the fresh performance of the mixture badly, but not in an equitable return.

3.2 Quasistatic compression test

The 56-day quasistatic compressive stress–strain curves of SCC containing different amounts of AE are presented in Fig. 5(a). From these curves, it can be seen that as the AE content increases, the compressive strength declines, while the deformation capacity of the concrete gradually improves. The peak stress declined as the AE content rose, whereas the peak strain increased, suggesting a shift towards a more ductile behaviour rather than a brittle behaviour. When the AE content reached 5%, 10%, 15%, and 20%, the compressive strength decreased by 7.87%, 9.21%, 28.10%, and 40.97% compared to the control mix, respectively. The strength loss of SCC was most evident as the AE content increased above 10%, implying that too much asphalt emulsion would detrimentally influence the load-carrying capacity of SCC. In this investigation, strength reduction is attributed mainly to the influence of the asphalt emulsion on the cement hydration process. Asphalt emulsion, in the presence of cement, began to demulsify and form a film of cohesive asphalt that encapsulated unhydrated cement particles, cement hydration products, and the surface of aggregate. The asphalt films partially inhibit cement hydration and form a thin film around the ITZ to impede further formation of hydrate and result in weakening the bonding at the ITZ between aggregate and cement mortar. Therefore, the compressive strength of the composite decreased. This conclusion is in agreement with other research [55, 56], stating that either the internal cohesion of asphalt or weakened asphalt–cement bonds play a decisive role in weakening asphalt-modified cementitious composites. Although the peak stress decreased, the postpeak response of the AE-modified mixtures showed a distinctly smoother postpeak slope in the descending branch of the stress–strain curve compared with the control SCC. This gentler postpeak slope reveals higher plastic deformation and slow crack propagation, which represent a ductile mode of failure. Therefore, asphalt emulsions have been demonstrated to improve the deformability and energy dissipation capacity in the postpeak region for SCC.

However, these improvements come at the cost of compressive strength, which is most apparent in the higher concentrations of AE. The study indicated that AE added at a concentration of 10% has the best balance between strength and deformability, which could be useful in some projects required to have a better resistance to stress and crack damage.

3.3 Toughness index

Fig. 5(b) shows that AE also affects the toughness index of the SCC mixtures. As can be observed, the toughness index has a tendency to increase as the dosage of AE increases, which shows that AE is indeed effective for improving the energy absorption capacity of SCC. The toughness indices are 5.21%, 17.00%, 24.13%, and 39.52% higher than that of the control mixture for specimens containing 5%, 10%, 15%, and 20% AE, respectively. This increase in toughness is mainly because asphalt has a viscoelastic property, which allows the improved cementitious matrix to undergo a large deformation while absorbing a large portion of mechanical energy when compression is applied.

During the process of demulsification of the asphalt emulsion, connected asphalt films will form in the matrix to bond the interface of hydration products and aggregates, which can function as a more elastic phase to postpone the cracking initiation, propagation, and distribution and postpone the further degradation capacity of the SCC after peak [27, 57]. Another benefit of having an asphalt film on the surface of the aggregates is to minimize stress concentration on the interface of aggregates and pastes and diminish the wedging effect of aggregates under loading. Thus, the stresses are better distributed in the matrix, which helps improve the deformation energy absorption of materials before failure. Similar toughening mechanisms are well documented for asphalt-modified cementitious materials in other related research [27, 57]. Even though the increase in toughness is most pronounced for AE content close to 20%, a sharp decrease in compressive strength resulted for high AE content. Regarding the strength, toughness, and practical use for structural applications, the optimal AE content seems to be approximately 10%. With such an amount of AE, the increase in toughness reaches as high as 17.00%, while the compressive strength and self-compactability are reasonable and applicable for engineering purposes.

Table 4. Results for fresh properties

Mix ID	Slump flow (mm)	J-ring flow (mm)	Δ SF (mm)	T_{50} (s)	Bulk density (kg/m ³)
SC0	630	622.5	7.5	6.7	2176
SC5	617	609.1	7.9	7.8	2301
SC10	620	612.2	7.8	7.9	2302
SC15	585	570	15	8.7	2296
SC20	562	543	19	10.5	2273

Note: T_{50} = slump flow rate; Δ SF = difference between slump flow and J-ring flow

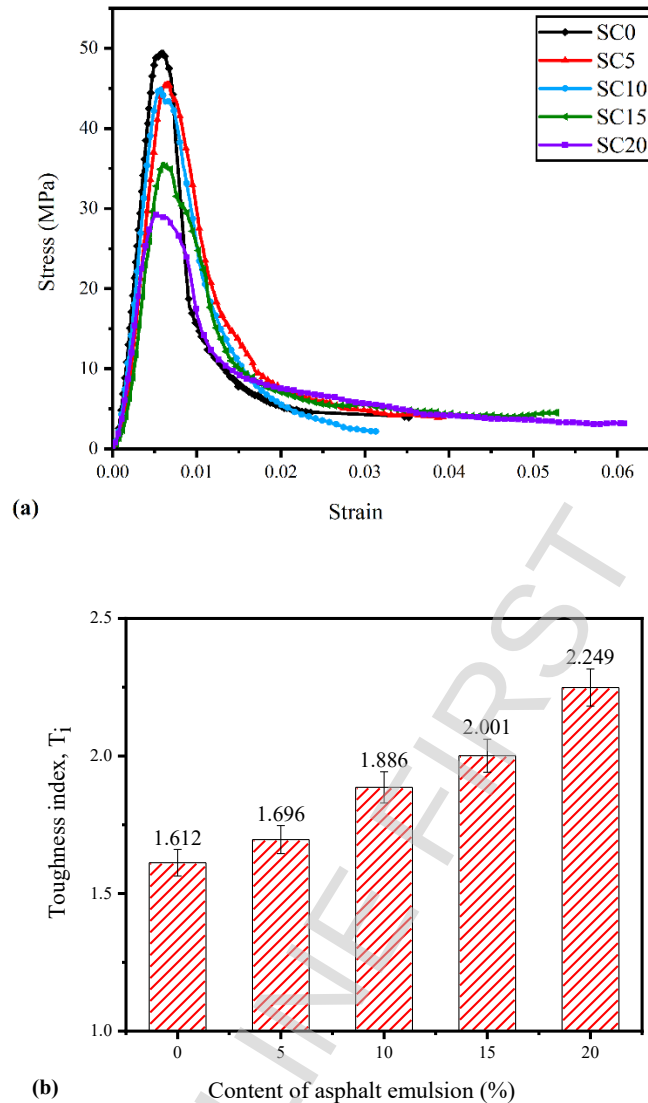


Figure 5. (a) Quasistatic stress–strain curves; (b) toughness index.

3.4 Pore structure

Fig. 6 presents the pore structure of the SCC specimens. The average pore diameter of the SCC decreases as the AE content increases. Specifically, the average pore diameter of the specimen with 5% AE is approximately 76% of that of the control specimen. When the AE content was increased to 10%, 15%, and 20%, the average pore diameter decreased further to 67%, 62%, and 57%, respectively, compared to the control set. This effect is also reflected in an increase in the pore spacing factor, as illustrated in Fig. 6(a), which is the maximum distance from any point within the hardened specimen to the nearest air void. The pore size distribution presented in Fig. 6(b) reveals that the pore content in the size range from 0 to 100 μm increased with the addition of AE, while the pore content in the size range from 100 μm to 1000 μm decreased with the addition of AE. Additionally, the content of pores with sizes ranging from 1000 μm to 3000 μm increased slightly as the AE content increased. That is,

the number of tiny pores increases, the number of medium pores decreases, and the number of large pores increases. The addition of AE retards cement hydration, resulting in fewer hydration products and a looser, more porous microstructure. However, free asphalt particles flow into the pores of the matrix, especially the medium-sized pores, which is why the pore content decreases in the range of 100 μm to 1000 μm . The increase in large pores due to AE contributes to improved toughness and decreased compressive strength, while the reduction in medium pores due to the filling effect of AE accounts for the decreased permeability of the SCC matrix. Moreover, it is important to note that the pore distributions for the control specimen are mainly within the range of 100 μm to 1000 μm , whereas a large percentage of pores in the AE samples are distributed within the range of 0 to 400 μm . As a result, the average pore diameter decreased, and the pore spacing factor increased for the groups with AE.

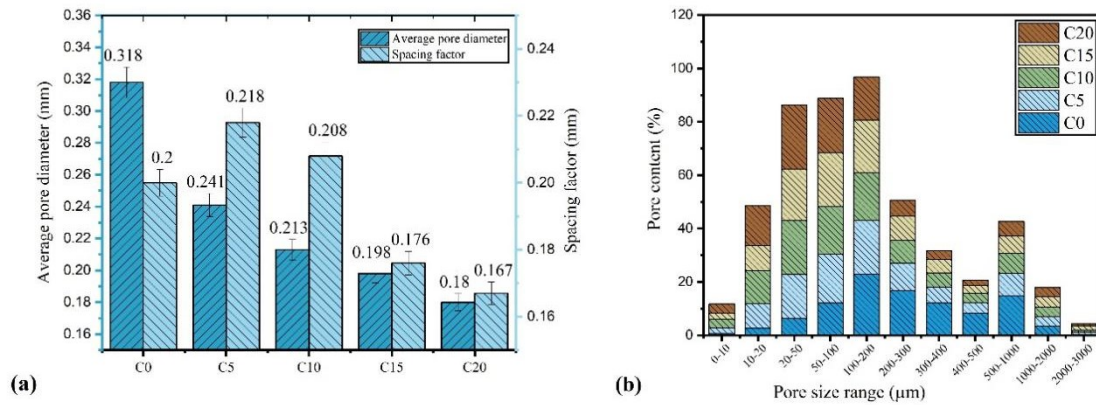
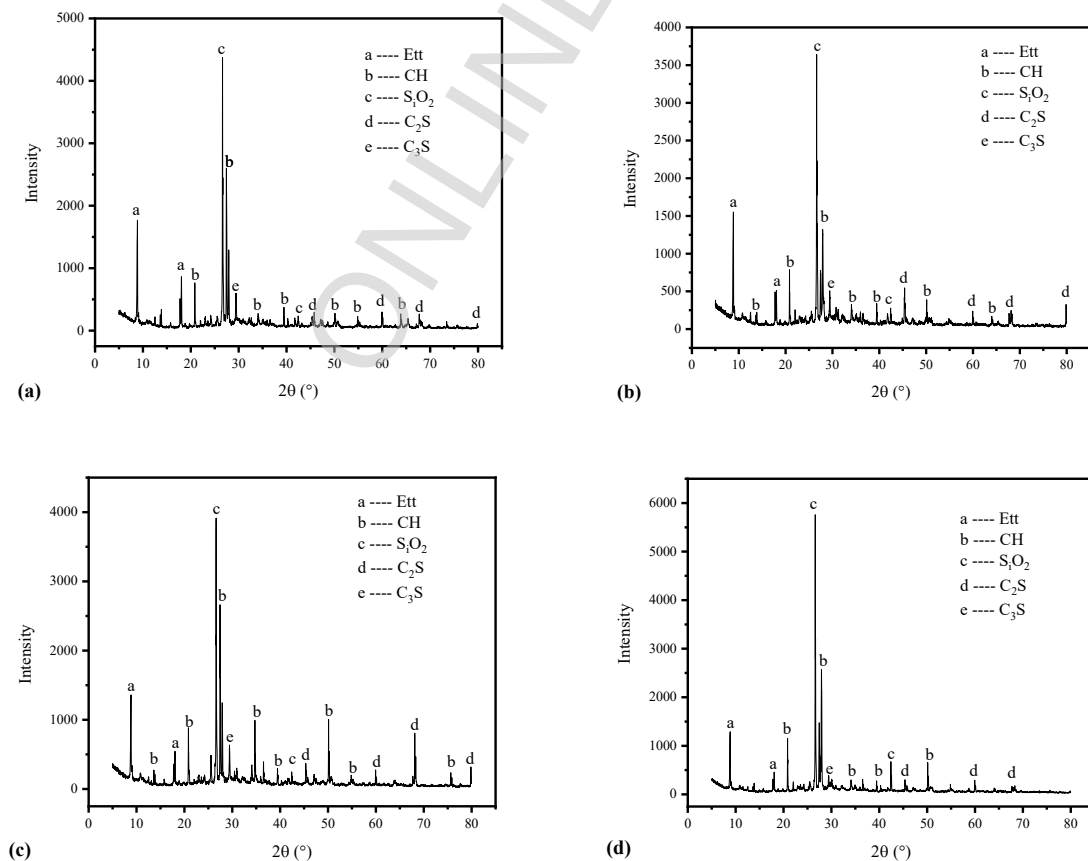


Figure 6. Pore structure of SCC specimens: (a) average pore diameter and spacing factor, (b) pore size distribution

3.5 X-ray diffraction (XRD) analysis

X-ray diffraction (XRD) analysis of the SCC specimens was carried out to determine the phase composition and qualitatively analyse the effect of AE on the hydration products of SCC. Fig. 7 presents the XRD results for SCC specimens with varying AE contents. The main products of cement hydration identified include ettringite (Ett), portlandite (CH), SiO_2 , C_2S , and C_3S . The figure shows that the XRD spectra of the specimens exhibit similar patterns as AE increases, with small discrepancies in trend. On average, the peaks of CH, C_2S , and C_3S decreased with the addition of AE. For example, in the spectra of C0, C5, and C10, the peaks were easily identified, whereas in the spectra of the specimens with 15% and 20% AE (SC15 and SC20), some

peaks disappeared. This can be attributed to the retarding effect of AE on cement hydration [58]. It was observed that with the addition of AE content, the hydration degree of cement decreases, thus resulting in a reduction in the amount of hydration products. However, according to the XRD results, it seems that the hydration products of the AE-modified specimens are almost the same as those of the reference mix. This result indicated that AE incorporation could not change the mineralogy and the type of hydration products [30] but could mainly reduce the hydration degree of cement, thus decreasing the amount of cement hydrate while retaining the original hydration mechanisms, and such a phenomenon accords with the results obtained from the compression test.



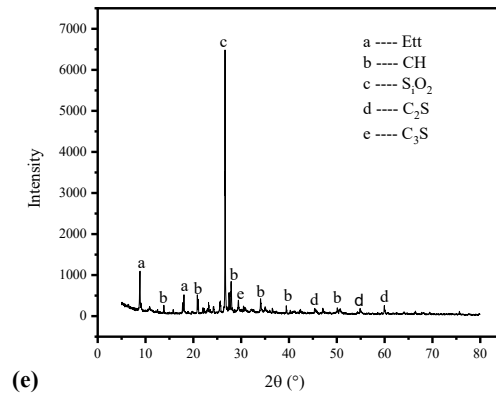


Figure 7. XRD of SCC samples with different amounts of AE (a) SC0 (0% AE); (b) SC5 (5% AE); (c) SC10 (10% AE); (d) SC15 (15% AE); (e) SC20 (20% AE).

3.6 Compressive strength

The compressive strength of the specimens at different curing periods is presented in Fig. 8. The figure indicates that asphalt emulsion deteriorates compressive strength of SCC specimens. However, the rate of the strength reduction declines with curing time; thus, the compressive strength improves with curing period. After 14 days of curing, the compressive strength decreased within the range of 15.6% – 39% due to the addition of 5 – 20% AE, respectively. After 28-day curing, the reduction in strength was within the range of 11.5% – 30.7%. Despite the effect of AE, adequate strength is achieved for all groups after 56 days of curing. The strength reduction is attributed to the retarding effect of AE on hydration process, which inhibits further hydration and, consequently, affects the formation of hydration products. Thus, with the addition of asphalt emulsion, the amount of hydrates produced during hydration of cement

decreased, which eventually led to the decrease in compressive strength [59].

3.7 Mathematical modelling

The accuracy of the model and the significance of the variables and their interaction with the response variables are usually evaluated using analysis of variance (ANOVA). After inputting experimental data and performing regression analysis, the RSM identified the quadratic models as the most appropriate for predicting the flowability and compressive strength of SCC. The proposed model equations for all the responses are given in Eqs. (6) and (7). The responses were determined using the proposed models. Table 5 presents ANOVA results for the effects of AE and curing time on flowability and compressive strength; Table 6 presents the models' validation results.

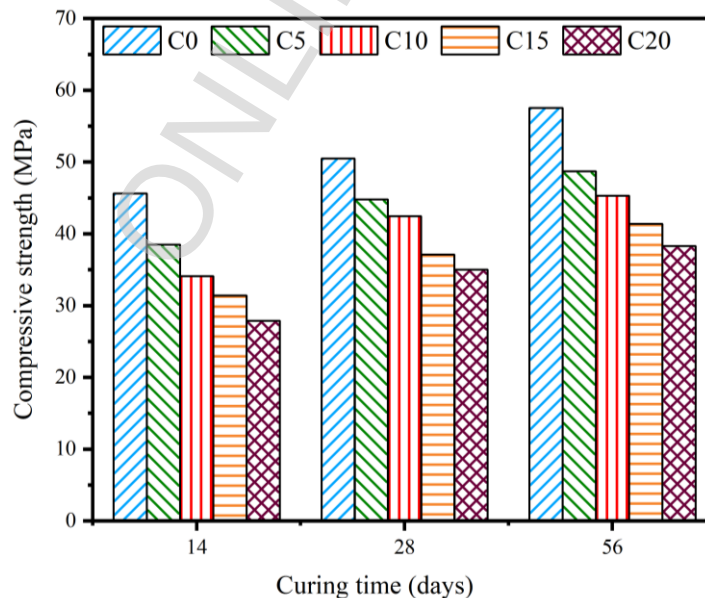


Figure 8. Compressive strength

$$SF = 627.985 + 0.694x - 0.2x^2 \quad (6)$$

$$CS = 35.818 - 1.321x + 0.729y + 0.000159xy + 0.0229x^2 - 0.00705y^2 \quad (7)$$

where SF and CS are the responses representing slump flow and compressive strength, respectively; x represents the content of the asphalt emulsion; and y is the curing time.

3.7.1 Verification of the proposed models

The models were verified using ANOVA at a 95% confidence level (i.e., 5% significance). Hence, any model or model term with a p value < 0.05 is statistically significant. The ANOVA results in Table 5 indicate that all proposed models are significant, with p values < 0.05 . For the model terms, x and x^2 are all significant for slump flow; for compressive strength, x , x^2 , y , and y^2 are significant terms, while xy is not significant; this indicates that AE content and curing time independently affect the compressive strength of SCC, according to the developed model.

Furthermore, Table 6 presents the validation parameters for all responses; the p values are all less than 0.05, indicating statistical significance. The accuracy of the proposed models can also be assessed through the coefficient of determination (R^2). High R^2 values of 0.96 and 0.992 are observed for slump flow and compressive strength, respectively. This indicates a higher degree of correlation between the predicted and actual experimental results and the model's validity in predicting the responses with high accuracy [60, 61]. Additionally, the predicted coefficient of determination (Pred. R^2) values match well with their corresponding adjusted coefficient of determination (Adj. R^2).

In addition, the adequate precision value assesses the signal-to-noise ratio of a well-developed model, with a minimum threshold of 4 required to ensure robustness [35, 62]. In this study, it is observed that all the proposed models achieved an adequate precision value of more than 4. This suggests that the models possess a high level of robustness and can effectively be used to navigate the design space.

3.7.2 RSM plot analysis for the influence of variables

In RSM, surface plots offer significant advantages for assessing potential relationships among variables. Fig. 8 shows the 3D surface plots and predicted-versus-actual plots for the influence of AE and curing time on compressive strength. The 3D surface plot shown in Fig. 8(a) provides insights into the effects of input variables on the output responses. It uses contour lines to display variations in the response under different levels and combinations of the independent variables. A color gradient is used to show the magnitude of responses in 3D plots, with red indicating the highest value and blue the lowest [62, 63]. Interestingly, the patterns observed from the plots are consistent with the experimental results. For example, the 3D surface plot of compressive strength shows a sloping-flat profile, indicating a well-established interaction between input variables [35, 61]. This underscores that the compressive strength decreases linearly with increasing AE content and increases

Table 5. ANOVA results for the response parameters

Response	Source	SS	DOF	MS	F value	p value	Significance
Slump flow	Model	8637.83	2	4318.92	118.5	<0.00001	Yes
	x -AE	7375.54	1	7375.54	202.36	<0.0001	Yes
	x^2	1075.2	1	1075.2	29.5	0.0003	Yes
	Residual	364.48	10	36.45	-	-	-
	Lack of Fit	364.48	2	182.24	-	-	-
	Pure error	0.0	8	0.0	-	-	-
	Cor Total	9002.31	12	-	-	-	-
Compressive strength	Model	1012.82	5	202.56	250.1	<0.0001	Yes
	x -AE	686.61	1	686.61	847.72	<0.0001	Yes
	y -time	254.44	1	254.44	314.14	<0.0001	Yes
	xy	2.34	1	2.34	2.89	0.1202	No
	x^2	19.39	1	19.39	23.93	0.0006	Yes
	y^2	24.77	1	24.77	30.58	0.0003	Yes
	Residual	8.10	10	0.81	-	-	-
	Lack of Fit	8.10	5	1.62	-	-	-
	Pure error	0.0	5	0.0	-	-	-
	Cor Total	1020.92	15	-	-	-	-

SS = Sum of squares; DOF = Degree of freedom; MS = Mean square

Table 6. Response model verification

Response	Slump flow	Compressive strength
R^2	0.960	0.992
Adjusted R^2	0.951	0.988
Predicted R^2	0.943	0.962
Adeq. precision	22.8	52.0
S.D	6.04	0.9
Mean	605.77	40.88
C.V%	0.997	2.2

S.D. = Standard deviation; C.V. = coefficient of variance

concurrently with extended curing time. The 3D surface plot of slump flow could not be obtained because only one variable, AE content, was included. Therefore, to graphically verify the model's adequacy, the predicted-versus-actual plot and the normal probability plot of the residuals (normal plot) were analysed and are presented in Fig. 9 (a and b). As shown in the figure, the data points were closely aligned with a straight line, confirming the accuracy of the developed model and the normal distribution of the data. The predicted vs actual plot for compressive strength is presented in Fig. 8(b). These plots illustrate the distribution of data points along the line of fit, and the degree of linearity among these points defines the accuracy of the models. The symmetrical distribution of data points along the line of fit suggests a strong correlation between the response model results and the experimental results [35, 61].

4 Conclusions

An experimental study was systematically performed on the effect of AE on the fresh properties, mechanical properties, and microstructural properties of SCC. A comparative result proved that AE is a good alternative to improve the toughness and energy absorption of the SCC and can also maintain a good fresh property in moderate AE content. The following conclusions were made based on the results of the experimental investigation and microstructure study.

1. Incorporating AE in SCC reduces workability, although the addition of up to 10% AE does not show a significant detrimental effect on flowability and passing ability. A higher AE content markedly reduces the workability of SCC.

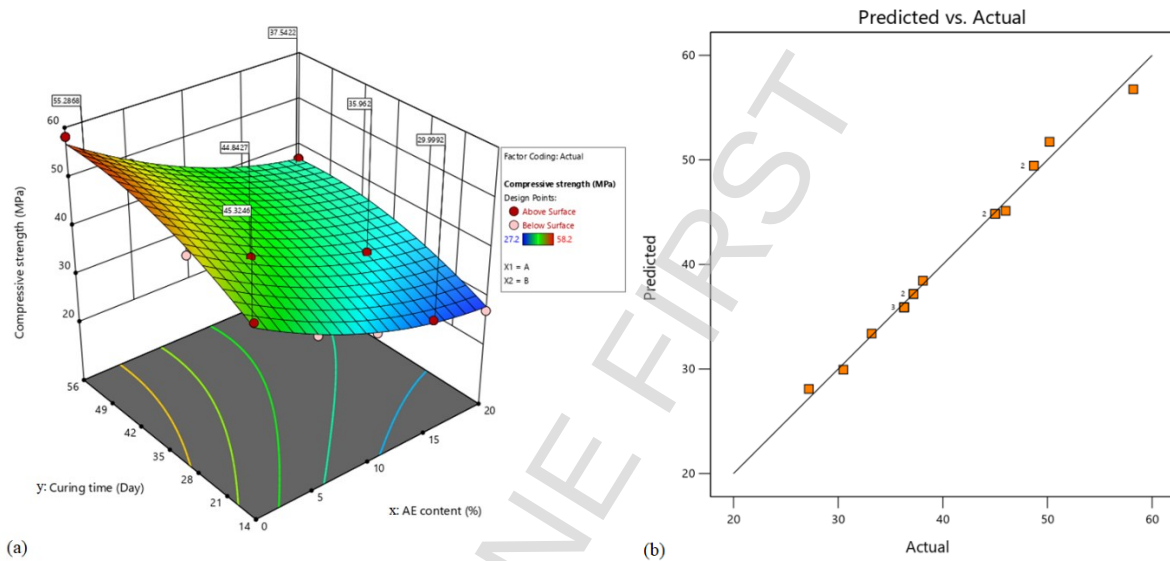


Figure 8. (a) Influence of AE and curing time on compressive strength: (a) 3D surface plot; (b) actual vs. predicted plot

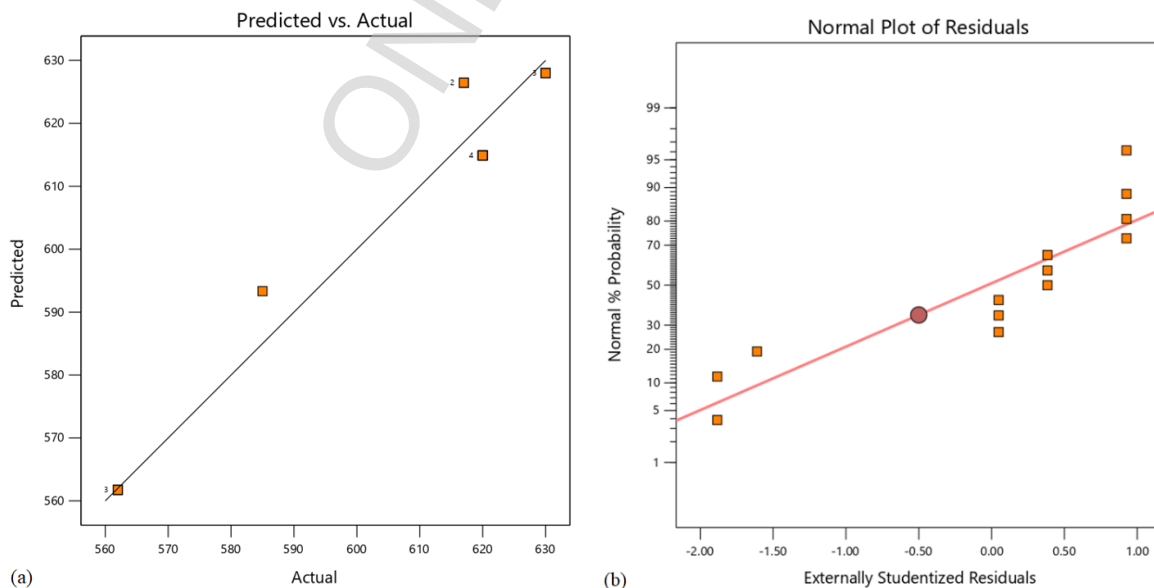


Figure 9. Effect of AE on slump flow: (a) predicted vs. actual plot; (b) normal plot of residuals

2. The addition of asphalt emulsion can decrease the peak compressive stress of SCC but also lead to a more ductile behaviour in terms of the development of the stress-strain curve: the postpeak part was much milder and more gradual, implying a much better deformation and energy absorption performance after postpeak fracture. This shows that the introduction of AE enhances the toughness and energy dissipation capacity of SCC, although the compressive strength is lower.

3. The toughness index of SCC specimens improves with the addition of AE. This implies that incorporating AE can effectively improve the impact resistance and energy absorption capacity of SCC.

4. The overflow asphalt particles penetrate and block up the pore system, which results in pore system refinement and improved compactness of the cementitious matrix. XRD tests indicate that the cement mineralogy and types of cement hydration products are not changed by introducing the asphalt emulsion; it decreases the hydration degree and thus the hydration product content but has no effect on the hydration mechanism.

5. Based on the experimental results from this study, the incorporation of 10% AE in SCC is recommended. This AE content has a favourable influence on energy absorption and toughness while maintaining the strength and excellent workability of SCC.

6. Mathematical models were established using RSM to predict the properties of SCC based on AE content and curing time. The models were validated using ANOVA, and all models achieved high R^2 (>0.9), a lower p value (<0.05), and strong agreement between the predicted and actual experimental results. Additionally, good agreement between the adjusted R^2 and predicted R^2 was observed, and the models had adequate precision greater than 4, indicating that they can be used to navigate the design space.

CRediT authorship contribution statement

Hussaini Abdullahi Umar and Ashiru Mohammed: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Roles/Writing - original draft. Luvuno Nkosingithi Jele, Aliyu Umar Mani, Ibrahim Aliyu, Zesizwe Ngubane, Jacob Adedayo Adedeji, and Nura Shehu Aliyu Yaro: Investigation; Methodology; Software; Validation; Visualization; and Writing - review & editing.

Declaration of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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