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PHYSICO-MECHANICAL AND DURABILITY CHARACTERISTICS OF SUPERSULFATE CEMENT CONCRETE ACTIVATED WITH SODIUM SULFATE INCORPORATING MARBLE WASTE

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ABSTRACT

The study evaluated the influence of marble waste as fine aggregate on the physico-mechanical and durability characteristics of supersulfate cement (SC) concrete incorporated with sodium sulfate to create an environmentally friendly concrete. The SC was formulated by combining ground granulated blast furnace slag with 10 wt.% sulfur trioxide (SO_3) from sodium sulfate as a sulfate activator and 5 wt.% ordinary Portland cement (OPC) as an alkali activator. Furthermore, marble waste is utilized as a partial replacement of natural fine aggregate in the variations of 0 wt.%, 15 wt.%, 30 wt.%, and 45 wt.%. Based on the research conducted, it was found that the substitution of natural fine aggregate using 45 wt.% marble waste provided supersulfate concrete exhibiting optimal physico-mechanical characteristics, achieving a compressive strength of 27.35 MPa and a flexural strength of 3.18 MPa. The durability characteristics demonstrated that the SC concrete incorporated with 45 wt.% marble waste fine aggregate substitution provided good quality concrete, evidenced by an ultrasonic pulse velocity (UPV) value of 4147 m/s, moderate chloride permeability reflected by an electrical surface resistivity (ESR) value of 15.3 kΩ.cm, and a total passing charge passing in the rapid chloride penetration test (RCPT) of 3558 Coulomb, indicating moderate chloride penetration.

Keywords: Durability, Marble waste, Physico-mechanical characteristics, Sodium sulfate, Supersulfate cement concrete, Sustainable concrete material

ABSTRAK

Kajian ini mengevaluasi pengaruh pemanfaatan limbah marmer sebagai agregat halus terhadap karakteristik fisik mekanis dan durabilitas dari beton supersulfate cement (SC) dengan natrium sulfat untuk menciptakan beton ramah limgkungan. SC diformulasikan dengan bahan dasar ground granulated blast furnace slag dengan 10 wt.% sulfur trioksida (SO_3) yang diperoleh dari natrium sulfat dan 5 wt.% ordinary Portland cement (OPC) sebagai aktivator alkali. Limbah marmer dimanfaatkan sebagai pengganti sebagian agregat halus dalam variasi yang ditentukan sebesar 0 wt.%, 15 wt.%, 30 wt.%, and 45 wt.%. Berdasarkan penelitian yang dilakukan, ditemukan bahwa substitusi agregat halus menggunakan limbah marmer sebanyak 45 wt.% menghasilkan karakteristik fisik mekanis yang optimal, mencapai kekuatan tekan sebesar 27, 35 MPa dan kekuatan lentur sebesar 3,18 MPa. Karakteristik durabilitas menunjukkan bahwa beton SC dengan substitusi sebesar 45 wt.% menghasilkan beton dengan kualitas baik, dibuktikan dengan nilai ultrasonic pulse velocity (UPV) sebesar 4147 m/s, permeabilitas klorida sedang yang ditunjukkan dengan nilai electrical surface resistivity (ESR) sebesar 15,3 kΩ.cm, dan total muatan pada rapid chloride penetration test (RCPT) sebesar 3558 Coulomb, yang menunjukkan penetrasi klorida sedang.

Kata kunci: *Durabilitas, Limbah marmer, Karakteristik fisik mekanis, Natrium sulfat, Beton supersulfate cement, Material beton berkelanjutan*

1. Introduction

Global warming and climate change have increased significantly due to greenhouse gas emissions, with the concrete-based construction sector contributing primarily to this rise. A substantial quantity of greenhouse gas is generated during the calcination process of clinker production in the cement manufacturing process [1]. Ordinary Portland Cement (OPC), the primary binding agent for concrete production, remains extensively used

across the construction sector. To minimize the harmful impact resulting from the utilization of OPC, it is crucial to develop alternative materials that can substitute cement for the development of eco-friendly concrete. The utilization of pozzolanic materials such as fly ash and ground granulated blast furnace slag (GGBFS) has predominantly been utilized as partial or complete replacements for OPC in the development of environmentally friendly concrete [2, 3]. Some studies showed that the activation of GGBFS with an alkali activator can effectively enhance the physico-mechanical properties of concrete. This phenomenon occurs because GGBFS has a low dissolution rate, which reacts with water poorly and requires the presence of an alkali activator to proceed appropriately and accelerate its hydration [4]. Furthermore, the activation of GGBFS with sulfates and alkalis has the potential to create a pore-inhibiting effect in OPC. The existence of sulfate could promote the formation of ettringite, consequently improving the properties of concrete and minimizing pore structure [5].

Supersulfate cement (SC) is an alternative eco-friendly cement consisting primarily of GGBFS in the amount of 70-90 wt.%, activated by the incorporation of both calcium sulfate ($CaSO_4$) at the amount of 10-25 wt.% and a small amount of alkali activators [6]. Several studies demonstrated that there are various types of sulfate activators applicable in the composition of SC. $CaSO_4$ is a sulfate activator that is commonly used in SC mixtures, which could increase the compressive strength and concrete durability when used at the appropriate dosage [7, 8]. Furthermore, phosphogypsum, a byproduct of the fertilizer industry, may serve as a sulfate activator in SC. Its application as a sulfate activator demonstrated an improvement in concrete durability when exposed to high sulfate exposures [9]. Additionally, when neutralized from its lime content, it contributes to the properties of fresh SC mixture [10]. Despite these benefits, phosphogypsum contains radioactive elements and requires calcination to achieve optimal reactivity with GGBFS [9]. Furthermore, sodium sulfate (Na_2SO_4) could serve as an alternative sulfate activator in SC, contributing to its wide availability and non-toxic characteristics. Na_2SO_4 is a white salt compound with a fine particle size and can be obtained naturally or from industrial manufacturing residues. Some studies indicated that the incorporation of Na_2SO_4 as a sulfate activator increases the physico-mechanical properties and durability of cement and fly ash-based concrete against sulfate attack compared to those without activation. In addition, at appropriate concentrations and water-to-binder ratios, sodium sulfate effectively contributes to the hydration process [11, 12].

The hydration process of SC still requires adequate alkaline conditions to ensure the optimal reaction. GGBFS-based cement mixtures require a minimal quantity of alkali activator to break down the surface layers on slag particles, facilitating the hydration of GGBFS. This activation promotes the formation of tobermorite (C-S-H) and ettringite, which are crucial for strength development and durability in SC mixtures [7]. Several studies have employed calcium oxide (CaO) or OPC as alkaline activators [13, 14]. Upon hydration, OPC or CaO undergoes decomposition of its compounds, resulting in the formation of portlandite ($Ca(OH)_2$), which promotes the dissolution and decomposition of GGBFS into silica and alumina. In SC mixtures, the OPC content, similar to other alkaline activators, typically does not exceed 5% [15]. Some studies have indicated that SC exhibits an excellent resistance to sulfate penetration [8, 9, 11]. However, its resistance to chloride ion exposure is relatively low. Due to high salt content, SC is less effective in preventing the ingress of chloride ions into the concrete, potentially resulting in the degradation of the steel reinforcement inside the concrete [16]. This phenomenon has drawn the attention of researchers investigating the chloride resistance of SC.

Marble is one of the most popular decorative materials utilized in building construction [17]. In the processing of marble stone for useful decorative products, cutting, honing, and polishing processes are required, which generate marble powder waste [18]. The valorization of marble powder waste has the potential to provide beneficial filling effects and produce a denser microstructure [19]. The utilization of marble powder waste has mainly been explored as a partial replacement of cement, as marble powder could improve the strength and durability of concrete [20, 21]. However, those studies mainly focus on utilizing marble powder for cementitious materials in concrete rather than replacing fine aggregate or applying it specifically in SC mixtures. Furthermore, most of these studies also focus on increasing the physico-mechanical properties of SC concrete rather than its resistance to chloride penetration, which is a main issue in SC concrete mixtures. The utilization of MWFA not

only provides an environmentally friendly substitute for fine aggregate but also enhances physico-mechanical properties in concrete mixtures, which is attributed to the greater cohesion between the MWFA and binder. In addition, MWFA exhibits beneficial properties, having a higher calcite ($CaCO_3$) content than other aggregates [22].Therefore, this study aims to assess the impact of utilizing MWFA in SC concrete mixtures on the physico-mechanical properties and durability, particularly its resistance to chloride penetration. In this study, the physico-mechanical properties of concrete were assessed on compressive and flexural strength. Meanwhile, the durability of SC concrete was evaluated using the electrical surface resistivity (ESR) and rapid chloride penetration test (RCPT). By incorporating MWFA to SC concrete mixture in this study, both the physico-mechanical properties and durability of SC concrete against chloride penetration are expected to improve.

2. Materials and Methods

2.1. Ground Granulated Blast Furnace Slag (GGBFS)

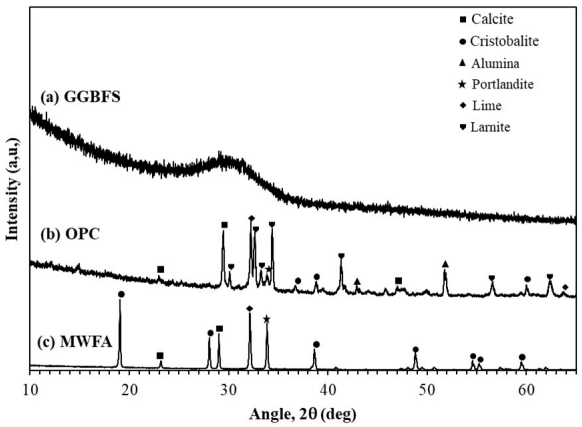
GGBFS that was utilized in this study was provided by PT KRT Green Indonesia and has a density of 2.82 g/cm³, which was determined according to ASTM C188 [23]. The GGBFS consists primarily of CaO and silicon dioxide (SiO_2) with percentages of 41.60% and 37.45%, respectively. The detailed chemical composition of GGBFS is presented in Table 1. In addition, the presence of a glassy structure is evidenced by a broad hump in the X-ray diffraction (XRD) pattern, observed within the 2θ range of 29° to 34°, as illustrated in Figure 1(a).

2.2. Ordinary Portland Cement (OPC)

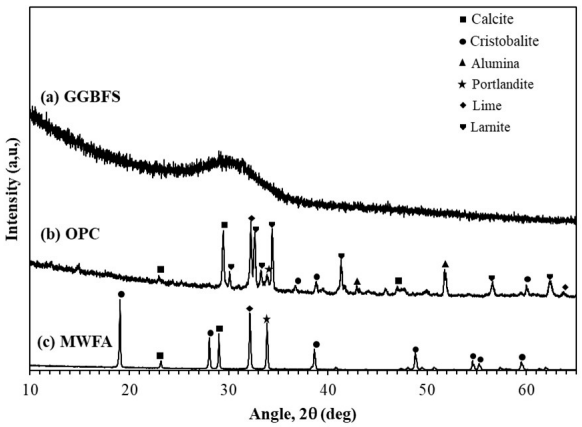
The OPC used in this study was locally sourced in Indonesia and had a density of 3.00 g/cm³, as determined using the Le Chatelier flask method in accordance with ASTM C188 [23]. Table 1 demonstrates that OPC used in this study is mainly composed of CaO, SiO_2, aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3). The XRD pattern of OPC, presented in Figure 1(b), demonstrated characteristic peaks of calcite ($CaCO_3$), lime (CaO), cristobalite (SiO_2), and alumina (Al_2O_3). In this study, OPC is employed as the alkali activator in the SC mixtures.

2.3. Sodium Sulfate (Na_2SO_4)

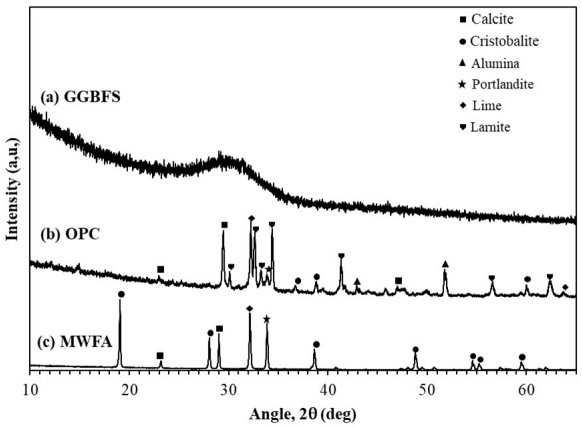
Na_2SO_4 used in this study was commercially obtained in Indonesia. It is an organic compound that appears as a white crystalline solid with a density of 2.61 g/cm³. This compound serves as a source of sulfur trioxide (SO_3) utilized as a sulfate activator in the SC mixture.



(a) GGBFS



(b) OPC



(c) MWFA

Figure 1. XRD Patterns of GGBFS, OPC, and MWFA

2.4. Natural Fine Aggregate (NFA)

This study utilized locally sourced natural fine aggregate (NFA), characterized by a specific gravity of 2.54 and an absorption rate of 4.99%, as determined by ASTM C128 [24]. The sieve analysis test was conducted in accordance with ASTM C136/136M [25]. As demonstrated in Figure 2, the gradation curve revealed that the NFA meets the ASTM C33/C33M classification. The fineness modulus of 2.41 indicates that the sand is very fine. Prior to use, the NFA was washed to eliminate organic impurities and was subsequently dried in an oven at a temperature of 110±5ºC for a minimum duration of 24 hours.

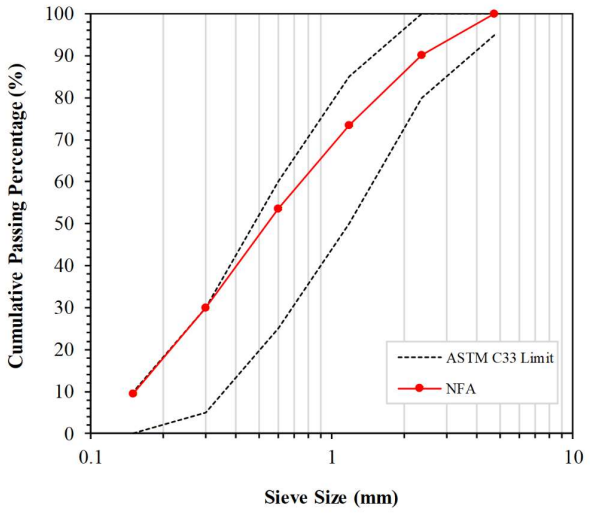


Figure 2. Gradation Curve of NFA

2.5. Coarse Aggregate (CA)

Locally sourced coarse aggregate (CA) was crushed in the laboratory by a stone crusher to achieve the maximum nominal aggregate size of 9.5 mm. Its specific gravity of 2.49 and an absorption capacity of 6.38% were determined according to ASTM C127 [26]. Before use, the CA was washed and dried in the oven at a temperature of 110±5ºC for at least 24 hours.

2.6. Marble Waste Fine Aggregate (MWFA)

Marble waste is collected from the local marble stone industry; the procedure of converting mined marble into functional pieces generates shards as a by-product of the cutting process. For preparing MWFA, the obtained marble waste was then sieved through an ASTM No. 4 sieve and dried in the oven for 24 hours. The MWFA has an irregular and coarser shape with an absorption capacity of 2.01% and most of the MWFA particles are retained in ASTM No. 8 and No. 16 sieves, which indicates a coarser gradation than NFA. From X-ray diffraction, it is shown that the marble waste is mainly composed of SiO_2, Al_2O_3, and CaO as shown in Figure 1(c).

Table 1. Chemical Composition of OPC, GGBFS, and MWFA

Chemical Compound	Percentage (%)		
	OPC	GGBFS	MWFA
Na_2O	0.26	0.03	0.97
MgO	2.41	1.03	0.60
Al_2O_3	5.39	16.25	25.30
SiO_2	18.10	37.45	64.60
P_2O_5	0.18	0.02	1.22
SO_3	3.26	1.73	0.17
K2O	0.81	0.33	1.21
CaO	65.70	41.60	3.72
Cr_2O_3	-	-	0.13
TiO_2	0.31	0.87	-
MnO_2	0,07	0.47	-
Fe_2O_3	2.95	0.62	1.21
ZnO	-	-	0.07
SrO	0.50	-	0.11
ZrO_2	-	-	0.14
Rh_2O_3	-	-	0.24
BaO	-	-	0.17

2.7. Mixture Proportion and Mixing Procedure

The SC concrete mixture was proportioned using the absolute volume method. The sand-to-aggregate ratio (S/A) was determined by applying the highest packing density approach through the blending of NFA and CA in various amounts. The packing density of blended aggregates was evaluated by adopting the procedure outlined in ASTM C29/C29M for determining the unit weight (*UW*) [27, 28]. As demonstrated in Figure, the test results indicated an optimum S/A of 0.65, obtained at the vertex of the regression curve. Subsequently, the SC formulation was determined based on the optimum performance as suggested in a previous study [29, 30]. GGBFS served as the primary constituent, with OPC incorporated as an alkali activator in the amount of 5 wt.% and SO_3 as a sulfate activator in the amount of 10 wt.%, equivalent to 17.75 wt.% of Na_2SO_4 based on the molecular weight. A water-to-binder ratio of 0.3 was selected based on preliminary experimental results to ensure a balance between desirable physico-mechanical properties and proper workability. A comprehensive study has shown that marble waste powder aggregate substitution of up to 40% creates a substantial increase in concrete

mechanical properties [22]. As the percentage increases, the mechanical properties of concrete tend to decline. Therefore, four mixtures were prepared by incorporating MWFA as a partial replacement for NFA by mass, at percentages of 0 wt.%, 15 wt.%, 30 wt.%, and 45 wt.%. These mixtures are designated as M0, M15, M30, and M45, respectively, as detailed in Table 2.

The mixing sequence of each SC concrete mixture was prepared by first dry-mixing the powder materials (GGBFS, Na_2SO_4, and OPC) with NFA only (for the M0 mixture) and with both NFA and MWFA (for M15, M30, and M45 mixtures), in the mixer for 2 min. Water was then gradually added and mixing continued until a homogeneous mortar was formed, followed by an additional 1 min of mixing. CA was subsequently added to the mixture and mixed for another 2 min until the concrete mixture became uniform. The fresh SC concrete mixture was then poured and cast into each cylinder and prism specimen molds and kept under laboratory ambient conditions. The specimens were demolded on the following day, then sealed cures in zipper bags and stored inside containers at ambient temperature the following day to prevent excessive moisture loss.

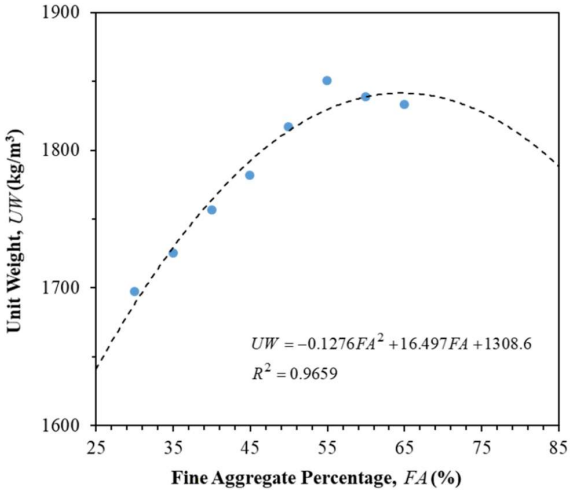


Figure 3. Unit Weight of Blended Aggregate with Various Fine Aggregate Percentage

Table 2. Mixture Proportion of SC Concrete Incorporating MWFA

Mixture Code†	Quantities* (kg/m³)						
	OPC	GGBFS	Na_2SO_4	Water	MWFA	NFA	CA
M0	26	403	92	156	0	1076	589
M15	26	403	92	156	161	915	589
M30	26	403	92	156	323	753	589
M45	26	403	92	156	484	592	589

†M = marble waste fine aggregate; the number denotes the percentage of substitution
*OPC = Ordinary Portland Cement; GGBFS = Ground Granulated Blast Furnace Slag; MWFA = marble waste fine aggregate; FA = natural fine aggregate; CA = coarse aggregate

2.8. Testing methodology

To evaluate the physico-mechanical properties of SC concrete, compressive strength was determined using a cylinder specimen with a dimension of 100 × 200 mm at the ages of 7, 14, and 28 days, in accordance with the ASTM C39/C39M [31]. Prism specimens with a dimension of 100 × 100 × 350 mm were prepared to determine flexural strength at 28 days, following ASTM C78/C78M [32]. Both tests were performed using a Universal Testing Machine (UTM). Furthermore, to assess the quality of SC concrete, the cylindrical specimens were also subjected to Ultrasonic Pulse Velocity (UPV) testing using a Portable Ultrasonic Non-Destructive Indicating Tester (PUNDIT) device according to ASTM C597 [33]. UPV measurements were conducted on the same specimens at 7, 14, and 28 days to monitor UPV development. Additionally, UPV testing was performed prior to compressive strength testing to investigate the correlation between UPV values and compressive strength.

Durability performance of SC concrete against chloride penetration was assessed using the ESR and RCPT methods. The electrical resistivity was measured on a cylindrical specimen with a dimension of 100×200 mm using a Wenner Probe Array, following the procedure outlined in AASHTO TP 95 [34]. Prior to testing, the specimens were brought to a saturated surface-dry (SSD) condition by immersing them in water for at

least one day. For RCPT, disc specimens (100 mm diameter and 50 mm thick) were prepared by cutting 100×200 mm cylindrical specimen with a concrete cutting machine. The sides of the specimens were coated with epoxy and submerged in aerated water under a vacuum of 50 mmHg, in accordance with ASTM C1202 [35]. Each specimen was then placed in an RCPT cell, where 0.3 N of NaOH and 3% of NaCl solutions were poured into the respective test cells. The test was conducted on each cell under a constant voltage of 60V. According to ASTM C1202 [35], the test should run for 6 hours; however, the test can be terminated automatically if the temperature of the solution exceeds 90ºC or the electric current exceeds 380 mA, as specified in the equipment manual.

After performing a 28-day compressive strength test, broken fragments from each specimen were collected and immersed in alcohol to stop the hydration process [36]. These fragments were then used for microstructure investigations, including XRD and SEM tests. The XRD test is aimed at determining the crystalline compounds formed during the hydration process of the SC concrete mixture. Since this test requires powdered samples, the alcohol-soaked specimens were first dried in an oven before being ground with a pulverizing machine to refine the powdered samples. The resulting powdered sample is then sieved through a No. 200 sieve and tested with XRD within a 2θ range of 15 – 65º. Meanwhile, the SEM test was conducted on tiny fragments to visually confirm the crystalline formation that was identified by the XRD test.

3. Results and Discussions

3.1 Compressive strength

Figure 4 demonstrates the compressive strength development at 7, 14, and 28 days of M0, M15, M30, and M45 mixtures with an early age strength of 6.35 MPa, 11.66 MPa, 13.71 MPa, and 12.71 MPa. At 28-day, all specimens achieved a compressive strength of 20.14 MPa, 25.34 MPa, 26.47 MPa, and 27.35 MPa, respectively, which shows a significant increase of 12.76 MPa to 14.64 MPa from the early age strength. The results reveal that the SC concrete mixture with MWFA substitution of 45 wt.% achieved the highest compressive strength of 27.35 MPa, which is approximately 41% higher than that of the control mixture without MWFA. This finding aligns with previous studies, which reported that the optimum substitution level of fine aggregate by marble powder is approximately between 40% to 50%, while a higher replacement percentage has a tendency to decline in compressive strength [37, 38]. This improvement is due to the fact that marble waste has a better ability to act as filler in concrete mixtures compared to NFA [22, 39]. The incorporation of the coarser MWFA tends to improve the gradation of fine aggregate, resulting in higher compressive strength.

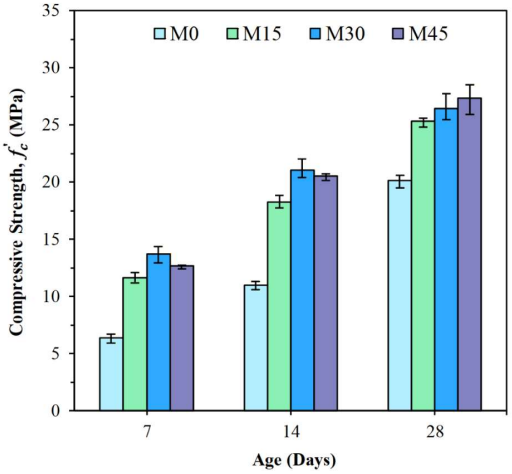


Figure 4. Compressive Strength of SC Concrete with Various MWFA Substitution Percentage

Although SC concrete mixture M45 gives the best compressive strength at 28-day, other mixtures seem to perform better at the early stage of concrete compressive strength development. Mixture M30 is shown to have a higher compressive strength than mixture M45 at 7-day and 14-day, while mixture M15 is shown to have an insignificant difference with mixture M45 at 7-day. This shows that the proportion of MWFA against NFA greatly affect SC concrete compressive strength development.

3.2. Flexural strength

Figure 5 demonstrates the flexural strength of M0, M15, M30, and M45 mixtures after 28 days of curing. Each mixture achieved a 28-day flexural strength of 1.78 MPa, 1.89 MPa, 2.15 MPa, and 3.18 MPa, respectively. This showed that the incorporation of MWFA in the SC concrete mixture could give the benefit of increasing the flexural strength of the concrete. The 28-day flexural strength of SC concrete with MWFA substitution at 45 wt.% reached 3.18 MPa, which a significant increment was observed to be about 78% higher than that of the control specimen without MWFA. This phenomenon confirmed that MWFA used in this study had a high composition of SiO_2, $CaCO_3$,

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and Al_2O_3 that could create additional C-S-H that could improve the cohesion between aggregate and binder [22, 39]. Interestingly, the substitution of NFA with MWFA at 45 wt.% benefits SC concrete flexural properties better than its compressive properties. This suggests that the improvement of cohesion between aggregate and binder significantly increases concrete's ability to resist flexural stresses.

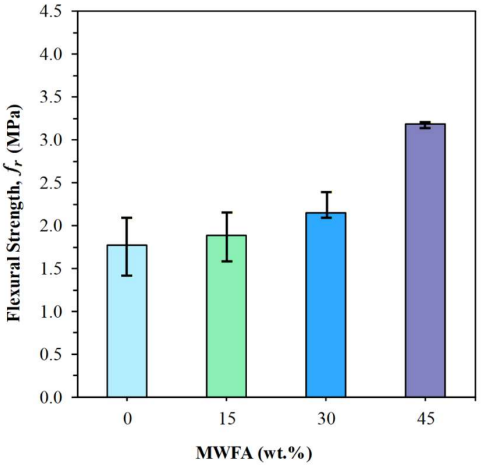

Figure 5. Flexural Strength of SC Concrete with Various MWFA Substitution Percentage at The Age of 28 Days

3.3. Ultrasonic pulse velocity (UPV)

The development of UPV values of SC concrete could be observed in Fig. 6. Regardless of MWFA substitution, it is proven that all SC concrete mixtures at 7 days reached the UPV values in the range of 3500 – 3900 m/s. Furthermore, at 28 days, the UPV values continued to increase by approximately 7 – 11% compared to the 7-day value.

Although the replacement NFA with MWFA only slightly enhances the UPV values, it is evident that the incorporation of MWFA can still maintain the SC concrete within a good quality range [40]. SC concrete with MWFA substitution of 45 wt.% exhibits a lower UPV value by 1.85% compared to the 30 wt.%. However, the differences in UPV values are not significant. Therefore, it can be concluded that SC concrete with 30% and 45% marble waste substitution exhibits comparable UPV values. UPV values can be correlated with other physico-mechanical properties of concrete, providing a reliable estimation without performing destructive testing [13, 41, 42].

An exponential equation, as written in Eq. (1), is commonly used to develop the relationship between compressive strength ($f_c^{'}$) of concrete and UPV value (V) with the parameters of a and b as constants.

$$f_c^{'} = ae^{bV} \quad (1)$$

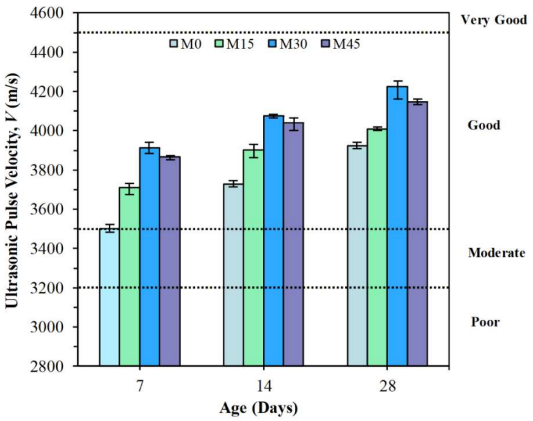

Figure 6. UPV Results and Quality Classification of SC Concrete With Various MWFA Substitution Percentage

The denser structure of the concrete may result from several factors, including the composition of the cementitious materials, the grading and size of both fine and coarse aggregates, and the interaction between the binder and the aggregates [41]. An exponential regression model was developed to describe the relationship between compressive strength and UPV for SC concrete incorporating MWFA. As also shown in Figure 7, this relationship is presented in Eq. (2).

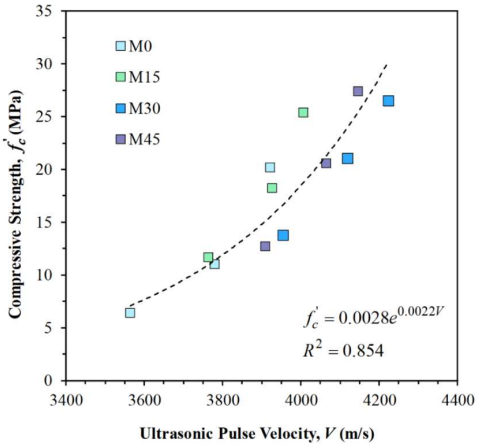

Figure 7. Relationship Between Compressive Strength and UPV of SC Concrete Incorporating MWFA

$$f_c^{'} = 0.0028e^{0.0022V} \quad (2)$$

This equation has a coefficient of determination (R^2) of 0.854, which indicates that the correlation derived from the regression analysis is valid for estimating or predicting the compressive strength of SC concrete based on UPV test results. Furthermore, as illustrated in Figure 8, the experimentally obtained compressive strength values exhibit no significant deviation from the predicted values, indicating that the proposed correlation demonstrated good accuracy.

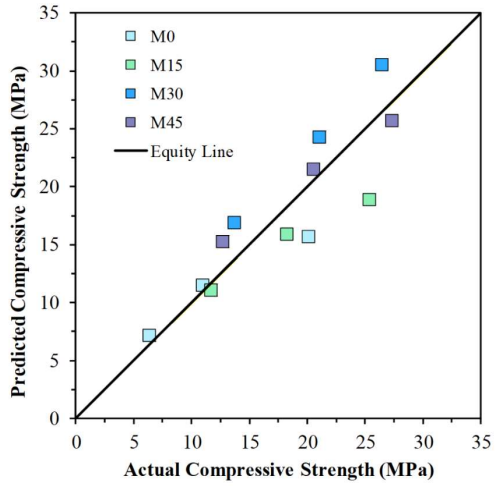

Figure 8. Comparison Between Modelled Compressive Strength and Experimental Compressive Strength

3.4. Electrical surface resistivity (ESR)

Based on several ESR studies, concrete incorporating SC exhibits lower resistivity values compared to conventional cement [16, 21]. This evidence indicates that, although SC has good sulfate resistance, its resistance to chloride penetration remains relatively poor. However, the incorporation of MWFA into the SC concrete mixture significantly enhances the resistivity, with increases ranging from 1.6 to 3.0 times. SC concrete without MWFA demonstrated an average resistivity of about 4 kΩ.cm, classifying it as highly penetrable concrete. In contrast, the substitution of MWFA in the amounts of 30 wt.% and 45 wt.% improves the resistivity to an average of 15 kΩ·cm, corresponding to a moderate penetrability classification, as illustrated in Figure 9. This improvement is primarily attributed to the reduction of void content in the concrete matrix [22, 39, 43, 44]. Beyond improving compressive and flexural strength, the filling effect of MWFA has been proven to effectively reduce the pores in concrete. This factor causes SC concrete with marble waste substitution to demonstrate higher resistance to sulfate penetration.

Several studies have shown that ESR values (ρ) can be correlated with compressive strength ($f_c^{'}$), since its properties are affected by the pore structures of the concrete [13, 45]. The proposed model adopts a logarithmic relationship as expressed in Eq. (3), where a and b are constants.

$$f_c^{'} = a\ln(\rho) + b \tag{3}$$

The experimental results demonstrated the relationship between ESR values and compressive strength, as shown in Figure 10 and the proposed equation obtained from logarithmic regression as given in Eq. (4). This correlation yields an R^2 of 0.985, which indicates a good correlation for estimating the concrete compressive strength based on ESR values.

$$f_c^{'} = 4.9748\ln(\rho) + 13.478 \tag{4}$$

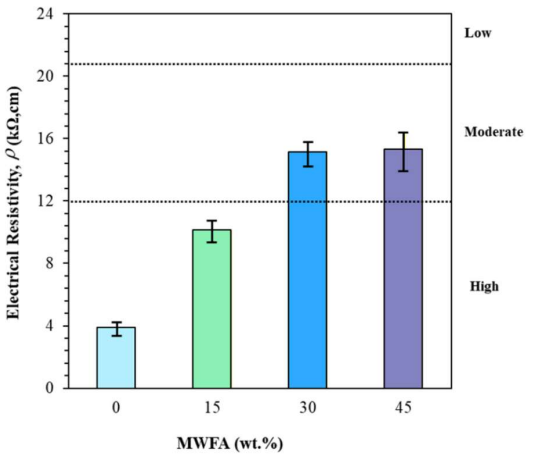

Figure 9. Electrical Surface Resistivity of SC Concrete with Various MWFA Substitution Percentage

3.5. Rapid chloride penetration test (RCPT)

The RCPT test was conducted over a period of six hours in accordance with ASTM C1202 [35]. The RCPT apparatus used in this study is equipped with two safety mechanisms to prevent damage to the test cell, where one mechanism interrupts the electrical current when the cell solution reaches 90°C and another mechanism halts the test when the current exceeds 380 mA. Some of the tests only lasted for 20–30 min before the machine terminated due to high electrical current. The RCPT interpretation can still be obtained by extrapolating the test data until the test termination time. The first

method for extrapolating the test data is by assuming that the total electric charge passing through the concrete remains constant over a duration of 30 min to 1 hour. Although it is a reasonable assumption, this method will result in a high total passing charge value due to the temperature rise that occurs during the duration of the test [46]. Bassuoni et al. (2006) proposed a method for extrapolating test data by multiplying the value of the electric current over a period of 30 min, assuming that during this duration, the transport of chloride ions through the concrete mix has reached a stable condition [46]. Although this method has been proven to have a lower total passing charge then the recorded data obtained from the test, it is highly dependent on the composition of the concrete mixture. Different mable powder content may affect the result of the extrapolation process. Nevertheless, both of these method is used to extrapolate the RCPT test data.

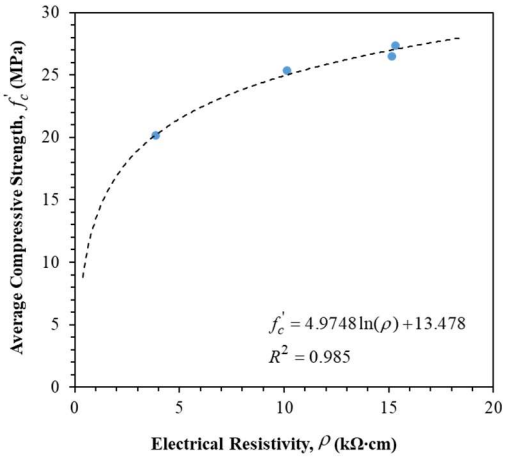

Figure 10. Relationship Between ESR Values and Compressive Strength of SC Concrete Mixture Incorporating MWFA

The RCPT results of M0, M15, M30, and M45 mixtures were analyzed with both extrapolation methods, as illustrated in Figure 11. The extrapolation using the second method (multiplying the 30-min current by 12) shows a total passing charge of 10212 Coulombs, 5280 Coulombs, 4386 Coulombs, and 3558 Coulombs, respectively, which is lower compared to the first method. The second method neglects the effect of temperature rise during the test period; a lower value of passing charge is expected, which is considered more accurate than the recorded data of passing charges and the extrapolation of the first method [40]. Furthermore, the experimental results indicated that SC concrete incorporating higher percentages of MWFA exhibited reduced charge pass. According to the extrapolated data as shown in Fig. 11, the total passing charge of the SC concrete mixture without MWFA was approximately 10000 Coulombs, which is double the charge recorded for the mixture containing 45 wt.% of MWFA. This result demonstrates that the inclusion of MWFA effectively reduces porosity in the concrete matrix, which is one of the key factors of chloride transport inside the concrete mixture [47].

Concrete resistivity values were obtained from RCPT at both 1-min and 30-min intervals of testing. A previous study suggested that concrete resistivity measured at 1 min provides more reliable results, since it minimizes the effect of temperature [46]. This trend is also observed in the present study, where the concrete resistivity of all SC concrete mixtures decreases from 4 kΩ.cm to 2 kΩ.cm, as presented in Table 3. When compared to the ESR test, the RCPT results showed similar resistivity values for all SC concrete mixtures, ranging from 3.3 to 5.4 kΩ.cm. These findings suggest that RCPT results are more sensitive to the presence of salt in SC concrete mixtures, whereas ESR measurements appear to be less affected by such factors [46, 48].

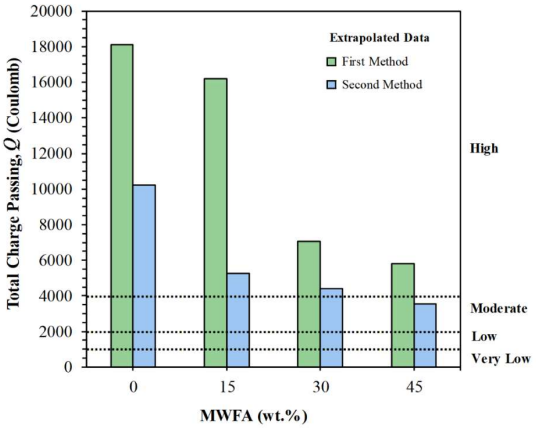

Figure 11. Extrapolated Total Charge Passing Through SC Concrete with Various MWFA Substitution Percentage

Several studies also indicated that ESR and RCPT have a correlation in a non-linear relationship [49]. Although a linear relationship is expected theoretically, experimental findings indicate that the total electric charge passing through concrete is inversely related to its resistivity or directly proportional to its conductivity, as illustrated in Fig. 10 [44, 49]. A polynomial inverse relationship between ρ, which is the electrical resistivity value

and total charge passing (Q) through the SC concrete is proposed in Eq. (5) with R^2 of 0.987. This correlation further demonstrates that SC concrete mixtures incorporating MWFA exhibit a lower total charge passing and higher electrical resistivity than those without MWFA.

Table 2. Comparison of resistivity value of SC concrete from RCPT and ESR

Mixture Code	Resistivity from ESR Testing (kΩ.cm)	Resistivity from 1 min RCPT (kΩ.cm)	Resistivity from 30 min RCPT (kΩ.cm)
M0	3.9	4.0	1.0
M15	10.2	5.0	1.0
M30	15.2	3.0	3.0
M45	15.3	5.0	3.0

$$Q = 45.56\rho^2 - 1422\rho + 15051 \quad (5)$$

3.6. Microstructural Analysis

Figure 13 presents the XRD patterns for all variations of the SC concrete mixture. The patterns indicate that the presence of ettringite and tobermorite (C-S-H) could contribute significantly to the improvement of compressive and flexural strength of the SC concrete mixture [5]. The hydration process of SC also leads to the formation of other compounds such as calcite ($CaCO_3$), anorthite ($CaAl_2Si_2O_8$), and gypsum ($CaSO_4.2H_2O$). Additionally, the presence of sulfate salts in the form of thenardite suggests chloride ions penetrate throughout the SC concrete mixture [50]. This observation aligns with the results of the ESR and RCPT, which show that the SC concrete mixture has limited resistance to chloride penetration. The presence of Al_2O_3 in MWFA enhances the formation of $CaAl_2Si_2O_8$ in the form of anorthite to densify the concrete matrix [43].

The SC concrete mixture incorporated with 45 wt.% MWFA substitution was chosen to confirm the presence of interlocking ettringite and tobermorite phases, as illustrated in Figure 14. The ettringite in the SC concrete mixture is identified by its characteristic needle-like crystalline morphology, typically found in the concrete [50]. In contrast, the tobermorite phase appears to form a denser microstructure located adjacent to the ettringite crystal structure. The application of Na_2SO_4 as a sulfate activator has facilitated the formation of ettringite, enhancing the physico-mechanical qualities of SC concrete; however, it concurrently generates many pores inside the hardened composite. Therefore, the presence of MWFA has indeed helped to reduce and fill the pore volumes inside the mixture of SC concrete, thereby improving both the physico-mechanical and durability properties of SC concrete.

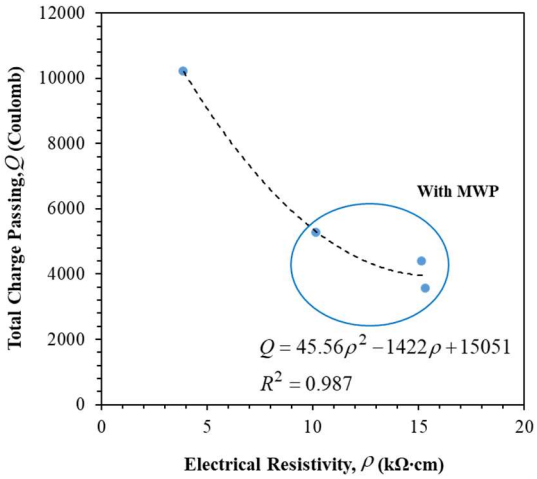

Figure 12. Relationship Between ESR Values and Total Charge Passing of SC Concrete with Various MWFA Substitution Percentage

4. Conclusions and Recommendations

This experimental investigation is aimed at examining the impact of substituting NFA with MWFA on the physico-mechanical and durability properties of SC concrete mixture. Based on the experimental results, the substitution of NFA with MWFA significantly improved the physico-mechanical properties of SC concrete. The highest compressive and flexural strength was observed at a 45 wt.% replacement level of MWFA, achieving values of 27.35 MPa and 3.18 MPa, respectively. This substitution has increased the compressive and flexural strength by 41% and 78%, respectively, when compared to the control specimen without MWFA.

The denser structure of the SC concrete mixture was found by incorporating MWFA, leading to an improvement in its UPV value. UPV testing indicated that the SC concrete mixture incorporating MWFA at a substitution of 45 wt.% exhibited a UPV value 5.7% higher than control specimens. The incorporation of MWFA produces good quality SC concrete with 28-day UPV values in the range of 3923 – 4225 m/s.

Durability assessments demonstrated that the presence of MWFA improves the resistance of SC concrete to chloride ion penetration. This was evidenced by an ESR value of 15.3 kΩ.cm categorized as moderate chloride permeability and

a total passing charge passing in the RCPT of 3558 Coulombs, indicating moderate chloride penetration, which is investigated at 28 days. Although both ESR and RCPT showed promising results, ESR is considered more effective in evaluating SC concrete mixture performance against chloride ion attacks, as it is less influenced by the salt contained in the mixture.

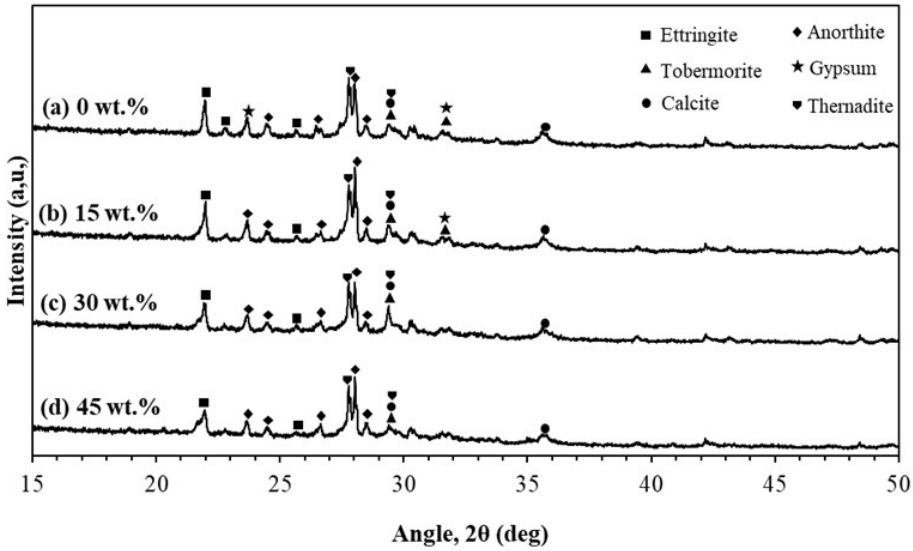

Figure 13. XRD patterns of SC concrete at 28 days with various MWFA substitution of (a) 0 wt.%; (b) 15 wt.%; (c) 30 wt.%; (d) 45 wt.%

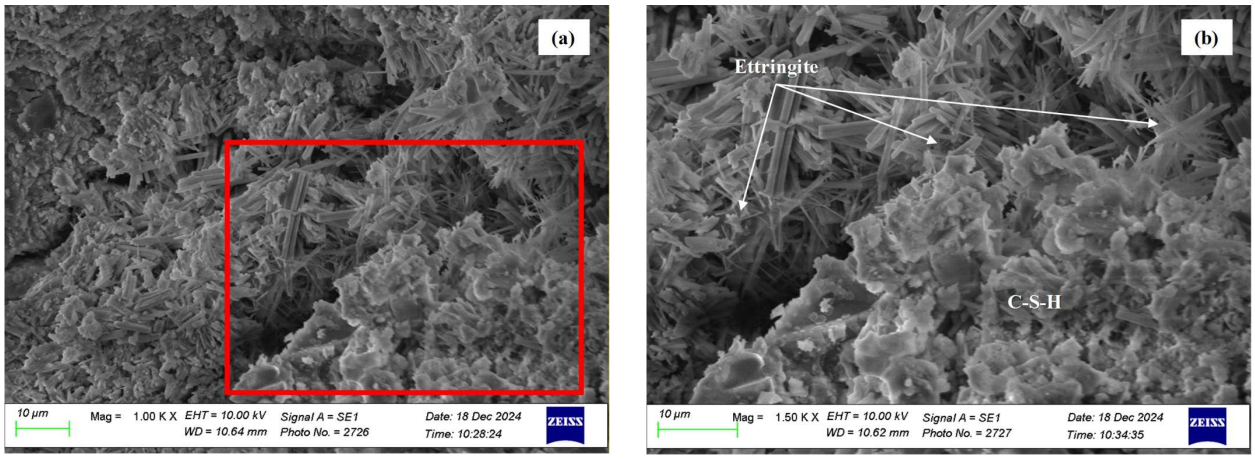

Figure 14. SEM Images of SC Concrete at 28 Days with a MWFA Substitution of 45 Wt.% under a Magnification of (a) 1000×; (b) 1500×

Acknowledgments

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