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RESEARCH ARTICLE

Rubber-Modified Self-Compacting Mortar: Evaluating Setting Time and Strength Development

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ABSTRACT

The influence of using crumb rubber (CR) obtained from the second scraping of used tires as fine aggregate in manufacturing self-compacting mortar (SCM) was investigated experimentally in this study. To explore this, natural fine aggregate in SCM mixes was partially replaced with CR at levels ranging from 5% to 25% by total fine aggregate volume. Two mix series, one with a total binder of 500 kg/m^3 and the other with a 540 kg/m^3 binder, were designed at water-to-binder ratios of 0.40 and 0.33. Ordinary Portland cement (80% by weight) and fly ash (20% by weight) were used to manufacture mortars. Twelve SCM mixes were cast and tested to evaluate their fresh-state properties, including setting times, flow diameter, and flow time. Moreover, the compressive strengths at 3, 7, 28, 56, and 90 days were determined for each mix to investigate their strength development. The test results indicated that the incorporation of CR adversely affected the fresh properties of the SCM mixes, and an increase in the CR replacement level systematically diminished their strength characteristics. Nevertheless, it was observed that it could be used in a controlled manner to achieve the desired properties.

Keywords: Compressive strength, Crumb rubber, High strength, Waste management, Workability

1. Introduction

Today, it is crucial to find convenient and efficient ways to produce more energy, minimize waste products, and reduce the use of natural resources. The increasing global demand for energy leads to significant waste contamination, highlighting the urgent need for innovative solutions that manage waste removal and help reduce carbon dioxide emissions in the atmosphere. Sending these wastes to disposal sites typically results in significant environmental problems. Therefore, recycling represents one of the most effective alternatives to waste disposal [1–3]. Due to their economic and ecological benefits, tires are among the most readily available products that can be easily recycled [4]. In recent years, heightened attention has been directed towards the proper disposal of tires, owing to the environmental hazards presented by waste tires [5, 6]. Notably, despite the large volume, only 19% of the 290 million scrap tires generated annually in the USA are recycled or repurposed for civil engineering applications. Additionally, scrap tires employed in such applications are often utilized as fill-in land reclamation or other large-scale earthwork projects, with only a small proportion being recycled and repurposed as artificial reefs or septic system drainage materials [7]. However, the utilization of waste tires remains insufficient, as current methods are not widely adopted or applied at a scale necessary to manage the entirety of tires produced [8].

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Recycling scrap tires is becoming an innovative approach, drawing increasing attention to its use in producing rubber-blended bituminous materials or as an additive in cement-based products [9, 10]. Recycling provides a practical solution for handling scrap tires by offering an eco-friendly alternative to conventional disposal methods like landfilling or burning, and it helps mitigate the negative impacts of global warming [5, 11–13]. Another advantage is improving concrete's energy absorption capacity, thereby mitigating its inherent issues of low deformation and poor tensile strength [14–17]. Although including tire rubber particles may adversely impact concrete's strength and workability, their inherent capacity to endure substantial strains represents a defining characteristic of these composite materials [1, 18]. This enhancement stems primarily from the increased plastic energy capacity that develops when tire rubber is incorporated, especially under impact loading [14].

For concrete to behave as self-compacting concrete (SCC), it must exhibit high fluidity and robust cohesiveness in its fresh state. Characterized by its ability to flow underweight, SCC fills formwork and achieves consolidation without compaction or vibration [5]. This is achieved by including a new-generation superplasticizer, which significantly enhances concrete fluidity [19, 20], while fine additives such as silica fume, slag, and fly ash (FA) substantially improve the stability of SCC. In another respect, the use of waste rubber as an aggregate can influence the features of SCC, affecting its strength, porosity, and flowability. Moreover, as a key phase of SCC, self-compacting mortar (SCM) similarly requires high fluidity under its weight for non-vibrated placement and effective pumping over long distances [14].

To this end, numerous studies have explored the impact of employing rubber derived from waste tires in manufacturing mortars and concrete. For example, Güneyisi [1] investigated the self-compatibility of rubberized concrete incorporated with FA by testing various fresh properties of the mixture. Yung et al. [5] replaced fine aggregate with tire rubber powder and subsequently assessed the durability characteristics and compressive strength. Additionally, Güneyisi and colleagues [11, 16, 19, 21] produced concrete using waste tire rubber and experimentally evaluated its effects on the workability, mechanical, and durability performances of the concrete. The studies above additionally investigated the role of mineral and chemical admixtures in SCC production. The test results revealed that rubber-modified concrete mixes demonstrated lower density, superior sound insulation, improved toughness and ductility, diminished strength performance (compressive and tensile), and augmented impact resistance [22–26]. Nevertheless, the application of surface treatment methods to the rubber particles has been shown to mitigate the detrimental effect of tire rubber on the strength of concrete [27]. On the other hand, according to the RILEM classification system, lightweight construction materials' fundamental limitations can be met with up to 50% tire particles [28].

The unique combination of lightweight properties, good sound absorption capacity, and favorable thermal characteristics positions waste tires as an alternative material for producing building elements that are both light and perform well in terms of acoustic and thermal insulation. In this context, prefabricated concrete wall panel systems, such as SmartWall (smart wall), stand out as industrial application examples where waste tire aggregate is used in addition to natural aggregate, differing from typical concrete production. These wall systems comprise panels approximately 10 cm thick with an angled, protruding surface. These angled and protruding surfaces reduce horizontal sound reflections, leading to better noise reduction performance. Furthermore, using color pigments during the concrete production of these panels allows for the creation of panels in various colors [29].

On the other hand, due to their lower mechanical properties compared to traditional concrete, concretes containing waste tires find use in non-structural applications. These primarily include lean concrete used for subbases, leveling, and filling, with acceptable low-strength expectations. Waste tire-reinforced concretes are also used as interlocking pavers for sidewalks and in producing anti-slip ramps. Another industrial application example of these concretes in road transportation is concrete barriers, which are explicitly used to separate vehicle traffic [30]. Moreover, due to the energy dissipation property of concretes produced with waste tire aggregate, these panels can be used as the outermost layer in producing bulletproof concrete slabs to enhance their effectiveness [31].

Previous investigations into using waste tire rubber in asphalt pavement applications have demonstrated promising results. However, the incorporation of waste tire rubber in concrete has not been as thoroughly investigated as its application in asphalt pavements [32]. While the utilization of waste tire rubber in concrete and mortar has been studied in previous works, a comprehensive understanding of its influence on SCM, particularly across a broad range of replacement levels (0% to 25% CR by volume of fine aggregate) and varying binder content/water-to-binder ratios (two distinct series), remains limited. This study addresses a critical knowledge gap by systematically exploring how CR modification impacts the fresh-state properties (including detailed flowability and setting time analyses) and SCM's long-term strength development (over 90 days) within these diverse mix designs. By providing detailed experimental insights into these specific SCM formulations, this research offers novel data crucial for optimizing sustainable and high-performance cementitious materials, directly contributing to more effective waste tire management and advanced construction practices.

This study conducted experimental investigations to explore the characteristics of SCM mixes modified with crumb rubber (CR). The fresh-state properties were evaluated, including flowability (assessed by slump flow diameter and V-funnel flow time) and set times (initial and final). Additionally, the study monitored the strength development of rubber-modified SCM over 90 days. For the mixed design, natural river sand functioned as a fine aggregate. CR waste was incorporated to partially substitute the sand at six distinct replacement levels, encompassing 0% to 25% of the fine aggregate volume. Twelve SCM batches were designed and manufactured, comprising two different series. For the first series of six batches, the total binder content and water-to-binder ratio (w/b) were 540 kg/m^3 and 0.33, respectively. For the second series, these values were 500 kg/m^3 and 0.40, respectively. Afterward, this study comprehensively analyzed and discussed the effect of CR on the properties of the SCMs through statistical evaluation based on the experimental outcomes.

2. Materials and methods

2.1. Materials

In this study, Portland cement (PC CEM I 42.5R), following TS EN 197-1 [33], was used as a primary binder, while FA, classified as Class F per ASTM C618 [34], was employed as a mineral admixture. The chemical compositions and physical properties of these materials are presented in Table 1. To achieve the target workability of the produced SCM, a polycarboxylic ether-based superplasticizer was incorporated into the mixes with a specific gravity of 1.07.

The fine aggregate used in plain and rubber-modified SCM mixes was natural river sand (NS), with a specific gravity of 2.39 and a maximum particle size of 4 mm. To produce rubber-modified SCM, CR obtained from scrap truck tires, discarded after a second recapping, was used as a replacement for NS. The specific gravity of CR adopted in this study was measured to be 0.60. The photographic view of CR and sieve analysis results of both NS and CR are respectively presented in Fig. 1a and Fig. 1b. As shown in Fig. 1b, both NS and CR exhibit very similar gradation.

Table 1. PC and FA: chemical compositions and physical properties.

Chemical analysis (%)	Portland cement	Fly ash
CaO	62.6	2.2
SiO_2	20.2	57.2
Al_2O_3	5.3	24.4
Fe_2O_3	4.0	7.1
MgO	2.8	2.4
SO3	2.7	0.3
K_2O	0.9	3.4
Na_2O	0.2	0.4
Loss of ignition	3.0	1.5
Specific gravity	3.15	2.0
Blaine Fineness(m^2/kg)	326	379

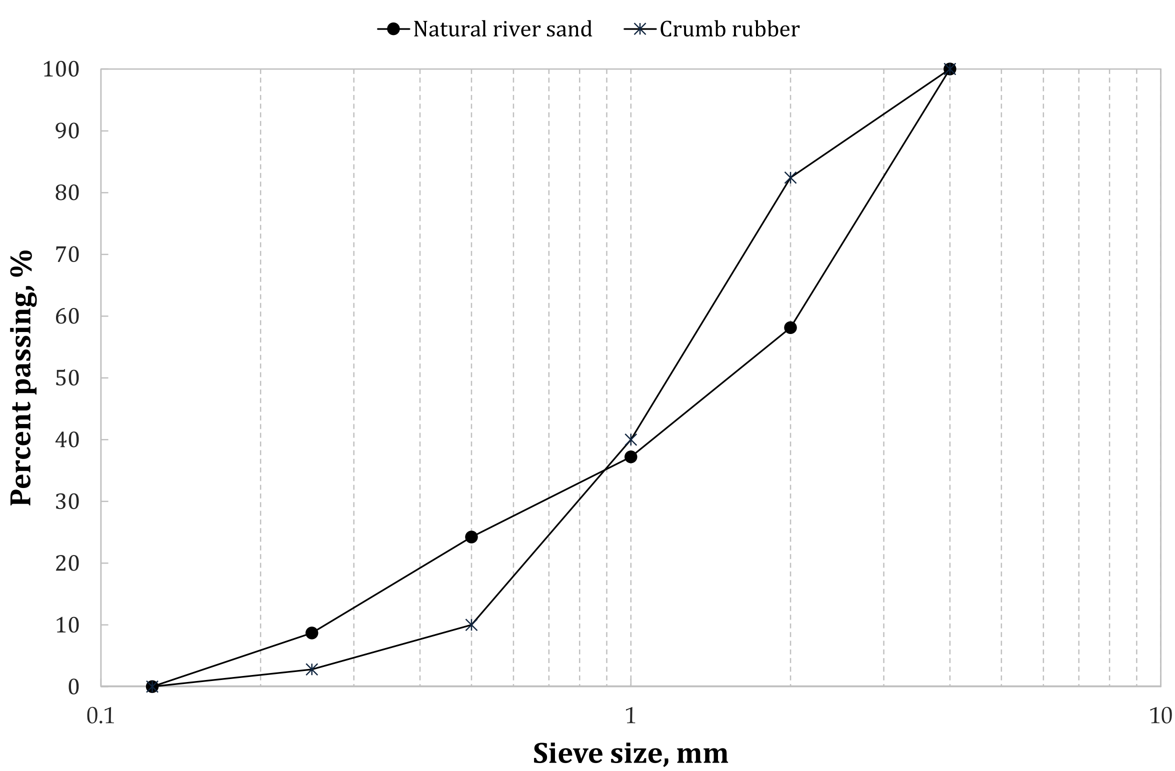
2.2. Mix design

In this study, two series of rubber-modified SCM mixes were designed. The first series had a water-to-binder (w/b) ratio of 0.33 and a Total binder content of 540 kg/m^3, while the second series had a w/b ratio of 0.40 and a binder content of 500 kg/m^3. In both series, the NS was partially replaced with CR at volumetric substitution rates of 0%, 5%, 10%, 15%, 20%, and 25%, calculated based on the total aggregate volume. Twelve SCM mixes were prepared to experimentally assess the effects of varying w/b ratios and CR replacement levels. Additionally, FA was incorporated at 20% of the total binder content to improve the mixes' mechanical performance and fresh properties. Table 2 presents the detailed mix proportions corresponding to each mortar mix ID. The mix designations reflect the specific composition of each mortar; for instance, the mix ID '33CR20' denotes a mortar with a w/b ratio of 0.33 and a CR replacement level of 20%. Moreover, trial batches were prepared for each mortar mix until the desired slump flow was achieved. The fresh properties of CR-modified SCM mixes were evaluated with a particular focus on flowability, which was assessed via mini-slump flow diameter mini-V-funnel flow time and setting time, which was determined using the penetration resistance test. Cube specimens measuring 100 mm were used to determine the setting times of the SCM mixes. Compressive strength development of plain and rubber-modified SCM mixes was assessed through compression tests conducted at 3, 7, 28, 56, and 90 days.

2.3. Mortar casting

An identical mixing and production procedure was employed throughout the experimental study to

(a)



(b)

Fig. 1. a) Image of CR and b) Sieve analysis results of NS and CR.

Table 2. Mix proportions of the rubber-modified SCM mixes (kg/m^3).

Mix ID	w/b	Cement	Fly ash	Water	Natural sand	Crumb rubber	Superplasticizer
33CR0	0.33	432	108	178.2	1503.5	0.0	8
33CR5	0.33	432	108	178.2	1428.3	18.9	8
33CR10	0.33	432	108	178.2	1353.2	37.9	8
33CR15	0.33	432	108	178.2	1278.0	56.8	8
33CR20	0.33	432	108	178.2	1202.8	75.8	8
33CR25	0.33	432	108	178.2	1127.6	94.7	8
40CR0	0.40	400	100	200.0	1491.1	0.0	5
40CR5	0.40	400	100	200.0	1416.6	18.7	5
40CR10	0.40	400	100	200.0	1342.0	37.6	5
40CR15	0.40	400	100	200.0	1267.4	56.6	5
40CR20	0.40	400	100	200.0	1192.9	75.2	5
40CR25	0.40	400	100	200.0	1118.3	93.9	5

ensure the production of SCM mixes with consistent uniformity and homogeneity. Initially, the NS and CR were dry-mixed in a standard laboratory mixer for approximately one minute to ensure uniform distribution. Subsequently, the dry ingredients were mixed with approximately half of the total mixing water, and the mixing continued for an additional one minute. The mix was left to rest for one minute to let the NS absorb the water. After the resting period, PC and FA were added to the mixture, and the mixing process was resumed for an additional minute. The remaining water and the superplasticizer were added, and the mixture was blended for three more minutes. The mixture was allowed to rest for two minutes, followed by a final mixing stage that lasted an additional two minutes. During the mini-slump flow test, potential signs of bleeding and segregation were closely monitored; however, none of the mixes exhibited these issues. After conducting the mini-V-funnel flow test, 100 mm steel cube molds were filled with fresh SCM mixes without any vibration or compaction in preparation for the setting time tests. Simultaneously, 50 mm cubes were cast and removed from the mold after 24 hours for the compressive strength test. A 21 ± 2°C water curing regime was applied to the specimens until the testing ages.

2.4. Methods of Testing

As mentioned earlier, the flow diameter and time of plain and rubber-modified SCM mixes were measured using two standard self-compatibility tests: the mini-slump flow test and the V-funnel test. The tests were conducted following EFNARC [35] specifications. The schematic presentation of the mini-slump flow test and the typical slump flow diameter measurement are shown in Fig. 2a and Fig. 2b, respectively. Additionally, Fig. 3 presents a schematic illustration of the mini-V-funnel flow time test apparatus.

Fig. 4a illustrates the testing apparatus for the penetration test, which was used to measure the setting times of the SCM mixes [36]. The setting time test

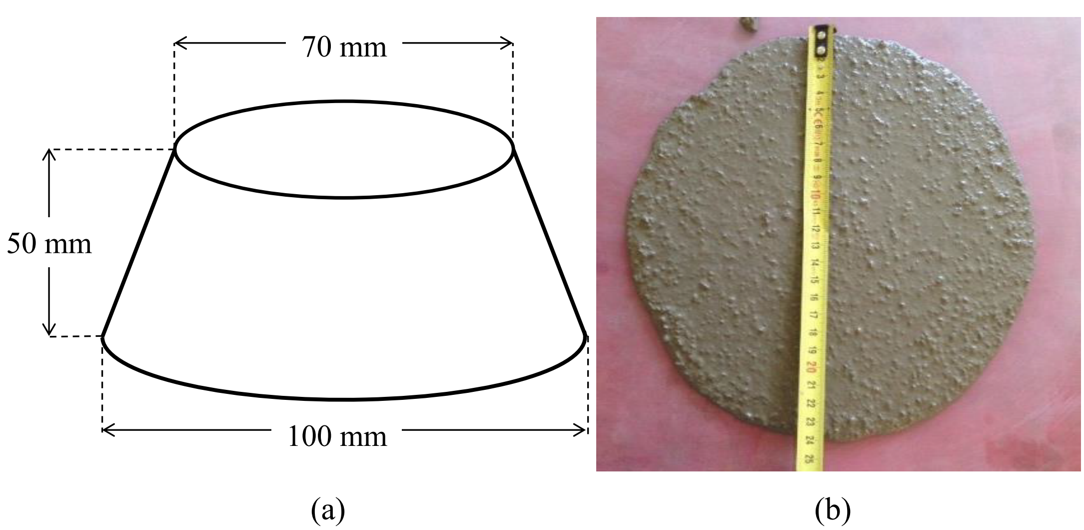


Fig. 2. Mini-slump flow test (a) illustration of test apparatus and (b) typical flow diameter measurement.

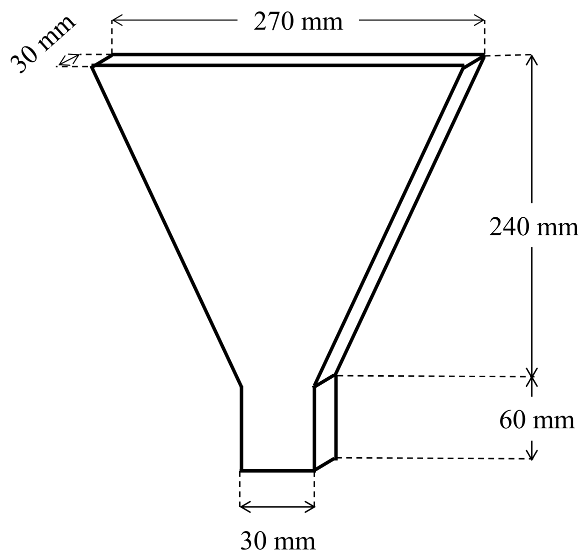


Fig. 3. Illustration of mini-V-funnel flow time test apparatus.

followed the ASTM C403 standard [37]. Although this test method is primarily used for evaluating the setting time of concrete, it can also be effectively applied to measure the penetration resistance of mortar mixes derived from concrete mixes [38]. The ELE penetration resistance device, featuring a spring reaction type, was used to measure the setting times of the SCM mixes, as shown in Fig. 4b.

During the test, the specimens were kept in a controlled environment with a temperature of approximately 20±2°C and a relative humidity of about 65±5%. As outlined in ASTM C403 [37], the initial setting time of the mortar mix is defined as the time it takes for the mix to reach a 3.5 MPa penetration resistance after the first contact between water and cement. The final setting time is determined by the time required for the mix to reach a 27.6 MPa penetration resistance [37]. The force during testing was recorded by allowing a standard needle with a 5 mm diameter to penetrate 25 mm into the SCM test specimens. This was done by recording the force at regular intervals during the testing. In the end, a time vs. penetration resistance chart was plotted to determine each SCM mix's initial and final setting times.

The compressive strength test was performed following the parameters set out in ASTM C109 [39], determined at curing durations of 3, 7, 28, 56, and 90 days, and the results were calculated as the average of three individual test samples.

3. Experimental results and discussion

3.1. Fresh-state properties of mortars

The flowability of rubber-modified SCM mixes. Specifically, their mini-slump flow diameter and mini-V-funnel flow time are presented in Fig. 5 and Fig. 6. Adjustments to the superplasticizer dosage allowed all mortar mixes to achieve an average

(a) (b)

Fig. 4. Penetration resistance (a) device and (b) used to measure the setting time [26].

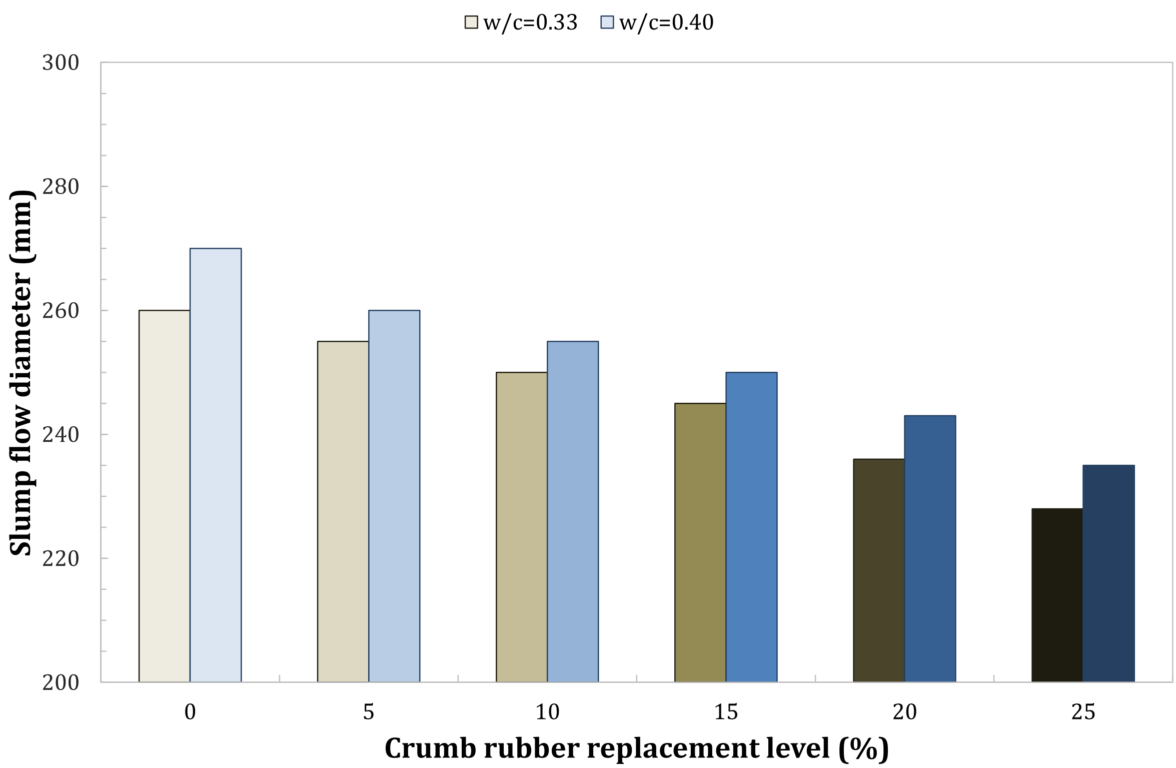


Fig. 5. Changes in the slump flow diameter of rubber-modified SCM mixes concerning the level of CR replacement.

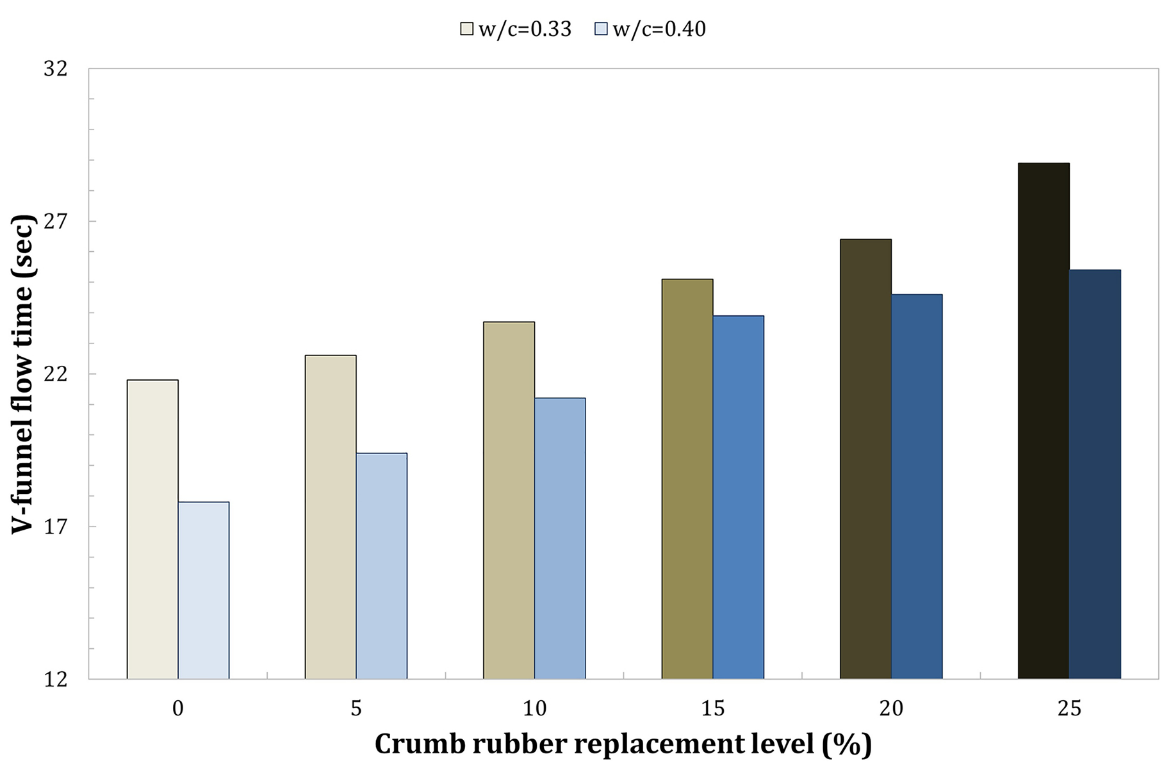


Fig. 6. Changes in the V-funnel flow time of rubber-modified SCM mixes concerning the level of CR replacement.

slump flow diameter of approximately 250±20 mm. Specifically, to fulfill EFNARC requirements, the superplasticizer dosage was adjusted when the w/b ratio increased from 0.33 to 0.40. The different levels of superplasticizer in the mix series may have influenced the other research parameters. However, the result indicates that the flowability of all rubber-modified SCM mixes was generally consistent with EFNARC standards [35]. For the plain SCM mixes, slump flow diameters were recorded as 260 mm for the first series and 270 mm for the second. Notably, despite a reduced superplasticizer dosage (from 8 kg/m^3 to 5 kg/m^3), the second series exhibited higher slump flow diameters (2-4% greater than the first series), primarily due to its higher w/b ratio.

The lowest slump flow diameters, 228 mm and 235 mm, were recorded for the 25% CR-modified SCM mixes in the first and second series. This 25% CR replacement level consistently showed the most significant decrease in slump flow diameter across all tested mixes (Fig. 5). Specifically, for CR replacement levels of 5%, 10%, 15%, and 20%, the slump flow diameters in the first series decreased by approximately 2%, 4%, 6%, and 9%, respectively. Second, these reductions were about 4%, 6%, 7%, and 10%. Increasing the CR replacement level from 0% to 25% resulted in approximately 12% and 13% decreases in slump flow diameter for mortars with w/b ratios of 0.33 (first series) and 0.40 (second series), respectively.

The reduction in flowability is primarily attributed to two factors: a decrease in the overall unit weight of the mixes due to CR incorporation and increased particle friction caused by the rough surface of the rubber particles. However, the magnitude of this decrease depends on both the rubber particle size and substitution level [40]. These findings align with previous research, indicating that CR incorporation increases the demand for superplasticizers to maintain adequate slump, leading to obstructed and reduced slump flow [1, 18, 19, 28, 41, 42]. Despite the decreased slump flow diameter, observations during mixing and casting confirmed that CR-incorporated mortar mixes remain workable compared to plain mortar mixes. Nevertheless, reducing flowability with increasing CR content persisted even when the w/b ratio was increased.

The absence of a strong bond between the mortar phase and CR particles, coupled with the significant difference in specific gravity between CR (0.60 in this study) and main ingredients like natural river sand (2.39), causes rubber particles to float upwards. This phenomenon leads to a high rubber concentration at the specimen's top layer, creating significant issues with key fresh properties, particularly during casting or vibration [43]. Experimental studies consistently show this as the segregation of rubber particles, with rubber floating and clustering at the surface, especially at higher CR contents. While fluidity generally increases with higher rubber content, this is often accompanied by an increased risk of segregation [44]. Consequently, increasing CR incorporation or dosage level leads to a decrease in slump flow diameter, directly reflecting the challenges in maintaining adequate fluidity in CR-incorporated mortars.

As depicted in Fig. 6, the V-funnel flow time of rubber-modified SCM mixes showed a trend inverse to that of the slump flow diameter. Specifically, as CR content increased, a delay in V-funnel time was observed, indicating a more sluggish flow, consistent with the slump flow results. For the plain SCM mixes, the shortest V-funnel flow times were recorded at approximately 22 seconds for the 0.33 w/b ratio and 18 seconds for the 0.40 w/b ratio. This confirms that the w/b ratio significantly influenced flow time. Notably, despite a reduction in superplasticizer dosage from 8 kg/m^3 to 5 kg/m^3 for the second SCM series (w/b ratio 0.40), these mixes exhibited lower V-funnel flow times compared to the first series (w/b ratio 0.33). The change in flow times between the two w/b ratios ranged from 5% to 18%.

At the 25% CR replacement level, the highest V-funnel flow times were recorded for both SCM series, reaching approximately 29 seconds for the 0.33 w/b ratio and 25 seconds for the 0.40 w/b ratio. This represents a substantial increase of roughly 33% and 43%, respectively, unequivocally demonstrating CR's significant influence on mortar fluidity. When analyzing the growth rates in flow times for CR replacement levels of 5%, 10%, 15%, and 20%, the first series mixes showed approximate increases of 4%, 9%, 15%, and 21%, respectively. These rates were considerably higher for the second series mixes: about 9%, 19%, 34%, and 38%. This indicates that the adverse effect of CR on flowability was more pronounced in mortars manufactured at a higher w/b ratio. The underlying reason for this phenomenon is that an increased w/b ratio reduces the mortar's cohesion and viscosity, consequently heightening the likelihood of CR particles separating and floating near the surface.

3.2. Setting times

Fig. 7 presents the rubber-modified SCM mixes' initial and final setting times. Setting time marks the transition from a fluid to a rigid state, defining the point at which stiffness develops in fresh concrete, a process driven by cement hydration [45]. In this study, CR consistently reduced stiffness across all modified SCM series. Both initial and final setting times were observed to increase with higher CR

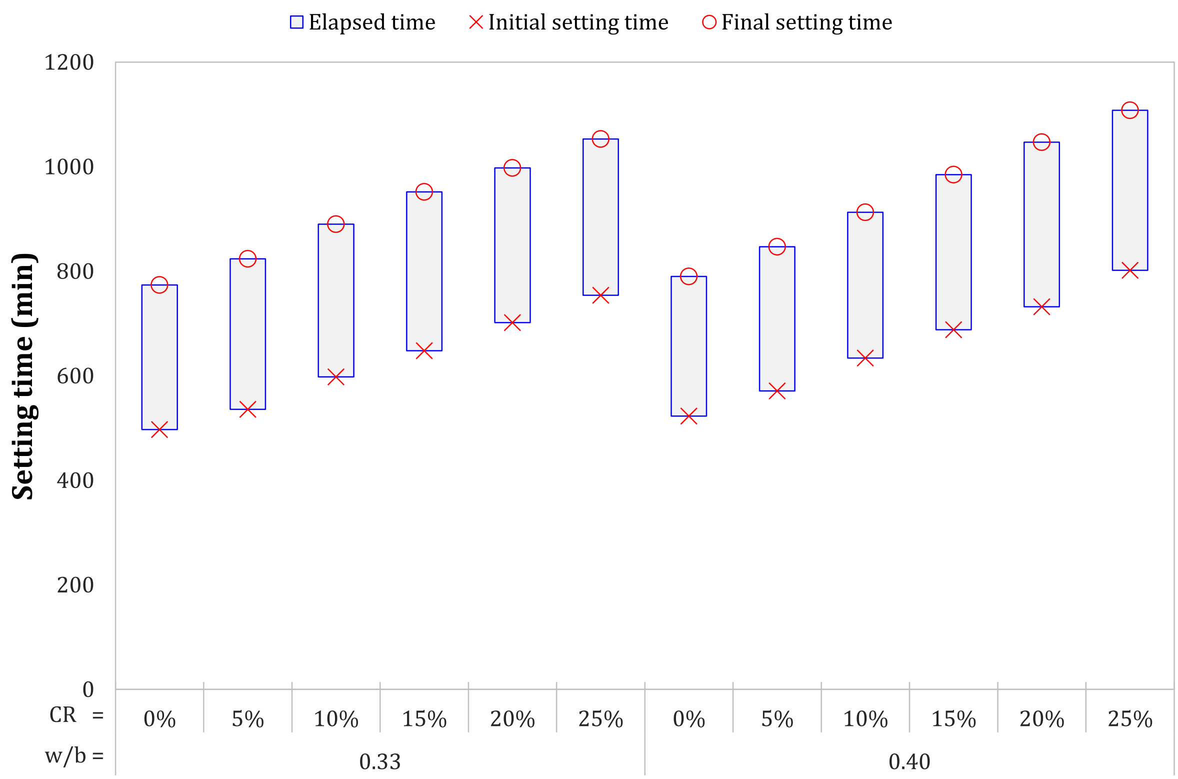


Fig. 7. Effects of w/b ratio and CR replacement level on setting times of rubber-modified SCM mixes.

incorporation levels. For instance, the plain mix in the 0.33 w/b series had an initial setting time of approximately 500 minutes. This increased to about 535 minutes at 5% CR replacement and significantly to 755 minutes at 25% CR replacement. A similar trend was observed in the 0.40 w/b series, where the plain mix's initial setting time of approximately 525 minutes extended to about 570 minutes at 5% CR and 800 minutes at 25% CR. Further analysis of these delays reveals the following percentage increases relative to their respective plain mixes:

- 0.33 w/b series: Approximately 8%, 20%, 30%, 41%, and 52% for 5%, 10%, 15%, 20%, and 25% CR replacement, respectively.
- 0.40 w/b series: Approximately 9%, 21%, 32%, 40%, and 53% for the same CR replacement levels.

These findings collectively indicate that CR incorporation retards the surface hardening of mortar, and this effect intensifies with increasing replacement levels.

Our findings, showing that increased CR replacement leads to longer initial and final setting times in fresh cement-based composites, are consistent with previous studies [1, 14, 19]. This observed retardation in setting times can likely be attributed to the presence of significant quantities (around 20%) of zinc in the chemical composition of rubber, as reported by Al-Akhras and Smadi [32]. Zinc is a known retarding agent for cement paste setting time [46].

On the other hand, a clear trend of delayed setting times (both initial and final) was observed in SCM mixes with higher water-to-binder (w/b) ratios despite a corresponding decrease in superplasticizer content from 8 kg/m^3 to 5 kg/m^3. For instance, the plain SCM mix with a 0.33 w/b ratio required approximately 500 minutes for the initial setting and 775 minutes for the final setting. In contrast, the plain SCM mix at a 0.40 w/b ratio showed a delay of about 25 minutes for the initial and 15 minutes for the final setting. This meant that initial setting times for the 0.40 w/b ratio mixes were 4% to 7% longer than for the 0.33 w/b ratio mixes, and final setting times were 2% to 5% longer. The final to initial setting times ratio for plain SCM mixtures was 1.56 (0.33 w/b) and 1.51 (0.40 w/b). This ratio consistently decreased with increasing CR replacement levels. For the 25% CR-replaced SCM mixtures, this ratio was approximately 1.40 (0.33 w/b) and 1.38g (0.40 w/b). The increased water content at higher w/b ratios slows down setting time and reduces mortar viscosity. This extra water can hinder the cement hydration process and the hardening of the surface.

3.3. Compressive strength development

Fig. 8a and Fig. 8b depict the compressive strength development of rubber-modified SCMs over 3, 7, 28, 56, and 90 days. Both plain and rubberized SCM mixes showed nearly identical strength development patterns. Strength gained rapidly between 3 and 7 days, with a more moderate increase from 28 to 90 days, indicating rapid early-age hydration followed by continued, slower strength gain.

Including (CR) consistently reduced compressive strength, irrespective of the curing duration or water-to-binder (w/b) ratio, with this reduction becoming more pronounced at higher CR replacement levels. For instance, while plain SCM mixes achieved approximately 96 MPa (0.33 w/b) and 89 MPa (0.40 w/b) at 90 days, incorporating 25% CR dropped strengths to roughly 41 MPa and 44 MPa, respectively. This 25% CR replacement ultimately led to a 40% reduction in compressive strength across both w/b ratios. However, it's notable that even with CR incorporation, mortars with up to 15% CR at a lower w/b ratio still achieved compressive strengths exceeding 70 MPa at 90 days.

The SCM mixes in this study exhibited high early-age strength, particularly within the first three days. For instance, the strength of the 0.33 w/b mortar series at 3 days was approximately 44-60% of its 90-day strength. As anticipated, mortars with a lower w/b ratio consistently showed superior compressive strength; a 7.3% increase in 90-day compressive strength was observed for the plain mortar when the w/b ratio was reduced. This improved performance at lower w/b ratios was observed across other rubber-modified SCM mixes. This phenomenon is primarily attributed to reduced capillary pore size and connectivity in SCM mixes produced at lower w/b ratios [46].

Strength development rates were also analyzed. A noteworthy finding from the compressive strength test was the consistent relationship between strengths measured at varying ages. For the plain 0.33 w/b SCM mix, the 90-day strength was approximately 1.24 times its 28-day strength, which in turn was about 1.13 times its 7-day strength. For the plain 0.40 w/b SCM mix, the 90-day strength was roughly 1.34 times its 28-day strength about 1.12 times its 7-day strength. For rubber-modified SCM mixes, the average ratios of 90-day to 28-day compressive strength were 1.26 (0.33 w/b) and 1.34 (0.40 w/b). Similarly, the average 28-day to 7-day compressive strength ratios were 1.13 and 1.16.

Beyond the quantity of rubber, CR's surface texture and particle size significantly influence compressive strength [47]. Consistent with numerous studies, incorporating waste-tire-derived rubber into mortar or concrete generally reduces mechanical performance compared to plain composites [1, 5, 19, 21, 43].

Mortar strength, particularly under compressive loads, is predominantly governed by the cementitious paste's quality, the aggregates' density and hardness, and the paste-aggregate bond's strength. CR particles, being less dense and softer than natural aggregates, compromise these factors. They act as stress concentrators and promote micro-cracking within the mortar matrix, decreasing strength [15, 38, 48]. Therefore, the primary causes for compressive strength loss in rubber-containing mortars can be summarized as follows [1, 5, 23, 43, 49]:

i. **Elastic Deformability and Stress Concentration:** Rubber is significantly softer and more elastically deformable than the surrounding cement paste. During loading, this stiffness mismatch causes stress concentrations around the rubber particles, leading to micro-cracks that propagate through the matrix quickly and accelerate structural failure.
ii. **Poor Interfacial Bonding and Void Formation:** The lack of strong bonding and implicit adhesion between rubber particles and the cement paste prevents even stress distribution. This results in a discontinuous matrix, making it prone to increased cracking at the aggregate-cement interface. The soft rubber particles can also effectively act as voids within the hardened mortar, compromising its integrity.
iii. **Non-Uniform Distribution (Segregation):** As noted previously, the tendency of rubber particles to float can lead to their non-uniform distribution within the mortar. This results in non-homogeneous cross-sections, where localized weaker areas can lead to premature failure under lower stresses.
iv. **Reduced Load-Bearing Capacity and Stiffness:** Due to their lower rigidity than natural aggregates, rubber particles reduce load-bearing potential and overall mass stiffness in rubberized mortars compared to plain mixtures.

In contrast to our findings, Al-Akhras and Smadi [32] reported increased mortar compressive strength with augmented CR content. They attributed this to the physical filler action of tire rubber, which created a more effective packing structure within the interfacial transition zone (ITZ) areas, leading to a smaller, denser, and more uniform ITZ.

Fig. 9a, Fig. 9b and Fig. 9c illustrate the relationship between the initial and final setting times and the 3-day, 28-day, and 90-day compressive strengths of CR-modified SCM mixes. The high coefficient of

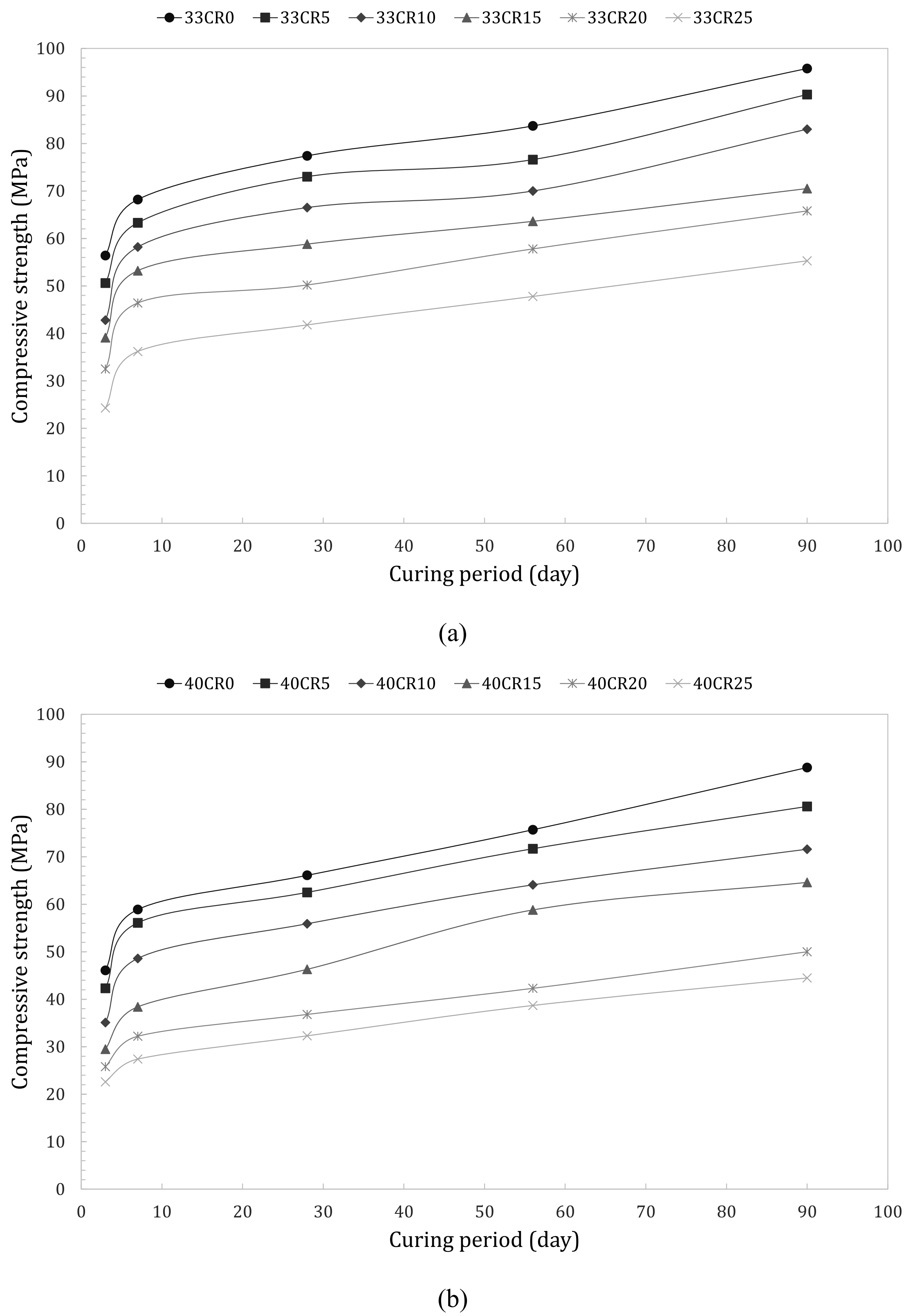


Fig. 8. Time-dependent compressive strength development of rubber-modified SCM mixes produced with w/c ratios of (a) 0.33 and (b) 0.40.

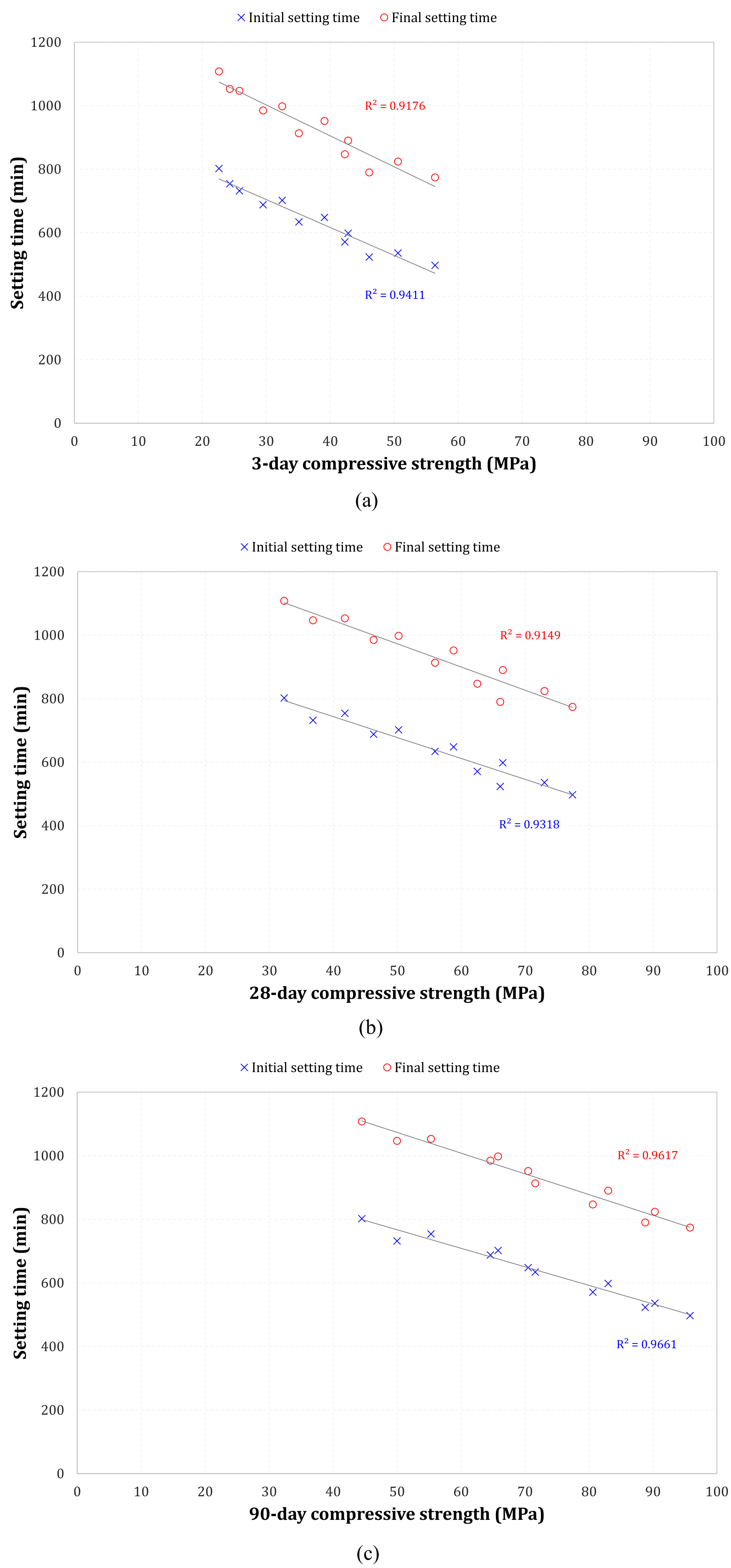


Fig. 9. Correlation between initial and final setting times and (a) 3-day, (b) 28-day, and (c) 90-day compressive strength values of rubber-modified SCM mixes.

determination (R^2) indicates a strong correlation between setting times and compressive strength. These figures clearly show an inverse relationship: as the compressive strength of SCM mixes increased, both initial and final setting times decreased.

3.4. Statistical evaluation of test results

Analysis of Variance (ANOVA) was employed to assess the statistical influence of experimental variables. Specifically, the General Linear Model Analysis of Variance (GLM-ANOVA) was utilized to evaluate the effects of independent variables on the discrepancies in the SCM mixes' fresh properties and strength and to determine the effectiveness of the testing parameters. GLM-ANOVA, a robust statistical tool, aids in minimizing error variance and identifying the dominance of controlling factors. This analysis designated compressive strength at various ages, mini-slump flow diameter, mini-V-funnel flow time, and setting times as dependent variables. Conversely, CR incorporation level and w/b ratio served as the independent variables. Each independent variable's contribution to compressive strength and fresh characteristics was subsequently calculated using the statistical analysis outputs. Table 3 presents the statistical analysis findings obtained from GLM–ANOVA.

Their P-values determine the statistical significance of experimental parameters on compressive strength and fresh characteristics. A parameter is considered an influential factor at a 95% confidence level if its P-value is less than 0.05. Additionally, the percentage contribution values indicate the relative effectiveness of each variable in influencing the tested response. These values are calculated by dividing an independent variable's sequential sum of squares by the total sequential sum of squares. A higher percentage contribution signifies a more dominant influence of that parameter on the evaluated characteristic [47].

GLM-ANOVA results ($P < 0.05$) confirmed that CR replacement level and w/b ratio significantly impacted SCM mixes' compressive strength and fresh characteristics. Analyzing the percentage contribution of independent variables revealed that the CR replacement level had a far greater influence on all dependent parameters, including flowability (flow diameter and time), setting times (initial and final), and compressive strength (at 28 and 90 days). CR consistently accounted for over 80% of the contribution for all investigated characteristics, demonstrating its substantial effect on mortar properties. Although the w/b ratio was a statistically significant factor, its contribution remained low, never exceeding 20%, and this influence did not vary considerably with the increasing w/b ratio.

Table 3. The results of GLM-ANOVA-based statistical evaluation.

Dependent Variable	Independent Variable	Sequential sum of squares	Computed F	P value	Significance	Contribution (%)
Slump flow diameter	CR content	14.7842	151.63	0.000	Yes	91.55
	w/b ratio	1.2675	65.00	0.000	Yes	7.85
	Error	0.0975	-	-	-	0.60
	Total	16.1492	-	-	-	-
V-funnel flow time	CR content	78.61	27.68	0.001	Yes	78.08
	w/b ratio	21.87	38.50	0.002	Yes	21.87
	Error	2.84	-	-	-	2.84
	Total	103.32	-	-	-	-
Initial setting time	CR content	101428	683.40	0.000	Yes	96.21
	w/b ratio	3852	129.77	0.000	Yes	3.65
	Error	148	-	-	-	0.14
	Total	105428	-	-	-	-
Final setting time	CR content	128634	209.36	0.004	Yes	97.05
	w/b ratio	3300	26.86	0.000	Yes	2.49
	Error	614	-	-	-	0.49
	Total	132548	-	-	-	-
28-day compressive strength	CR content	1879.23	367.75	0.000	Yes	82.88
	w/b ratio	383.07	374.82	0.000	Yes	16.89
	Error	5.11	-	-	-	0.23
	Total	2267.41	-	-	-	-
90-day compressive strength	CR content	2655.36	85.55	0.000	Yes	88.74
	w/b ratio	306.03	49.30	0.001	Yes	10.23
	Error	31.04	-	-	-	1.04
	Total	2992.43	-	-	-	-

V	w/b	RC	SF	Vf	IST	FST	f_c 3-day	f_c 7-day	f_c 28-day	f_c 56-day	f_c 90-day
w/b	1	0	0.280	-0.460	0.191	0.158	-0.357	-0.428	-0.411	-0.297	-0.320
RC	0	1	-0.953	0.870	0.980	0.985	-0.923	-0.893	-0.905	-0.940	-0.941
SF	0.280	-0.953	1	-0.962	-0.881	-0.891	0.776	0.733	0.747	0.813	0.807
Vf	-0.460	0.870	-0.962	1	0.766	0.788	-0.642	-0.599	-0.605	-0.681	-0.675
IST	0.191	0.980	-0.881	0.766	1	0.997	-0.970	-0.958	-0.965	-0.977	-0.983
FST	0.158	0.985	-0.891	0.788	0.997	1	-0.958	-0.950	-0.957	-0.976	-0.981
f_c 3-day	-0.357	-0.923	0.776	-0.642	-0.970	-0.958	1	0.979	0.983	0.965	0.974
f_c 7-day	-0.428	-0.893	0.733	-0.599	-0.958	-0.950	0.979	1	0.996	0.977	0.981
f_c 28-day	-0.411	-0.905	0.747	-0.605	-0.965	-0.957	0.983	0.996	1	0.983	0.989
f_c 56-day	-0.297	-0.940	0.813	-0.681	-0.977	-0.976	0.965	0.977	0.983	1	0.993
f_c 90-day	-0.320	-0.941	0.807	-0.675	-0.983	-0.981	0.974	0.981	0.989	0.993	1

Fig. 10. Correlation matrix of dependent and independent experimental parameters (V: variables; w/c: water-to-cement ratio; RC: rubber content; SF: mini-slump flow time; Vf: mini-V-funnel flow time; IST: initial setting time; FST: final setting time; f_c: compressive strength of mortar).

Beyond GLM-ANOVA, Principal Component Analysis (PA) was performed to comprehensively monitor the relationships and interactions among all experimental parameters and outputs. Fig. 10 illustrates these results.

PCA revealed strong correlations among the dependent variables:

- A strong positive correlation existed between the setting time and compressive strength of rubber-modified SCM mortars.
- Initial and final setting times were positively correlated (0.997), indicating an almost perfect relationship.
- Slump flow diameter and V-funnel flow time showed a high inverse interaction (-0.962).
- Slump flow diameter exhibited an inverse interaction with setting times, while V-funnel flow time had a moderate direct relationship with setting times.

Furthermore, PCA elucidated the influence of the independent variables on the experimental outcomes. The CR replacement level demonstrated a significantly strong interaction with all results: flow diameter and compressive strength decreased as CR content increased, while flow time and setting times increased. In contrast, the w/b ratio exerted a relatively minor impact on the experimental outcomes.

4. Conclusions

This research experimentally investigated the fresh-state and strength characteristics of SCM mixes modified with various levels of CR and two distinct w/b ratios. The key findings are as follows:

- CR consistently reduced the slump flow diameter and increased the V-funnel flow time of SCM mixes, indicating decreased flowability. These effects became more pronounced with increasing CR content. Despite this reduced flowability, all rubber-modified SCM mixes remained workable and usable compared to plain mixes. Similarly, a decrease in the w/b ratio from 0.40 to 0.33 reduced the mini-slump diameter and extended mini-V-funnel flow time.
- CR incorporation significantly extended the SCM mixes' initial and final setting times. For instance, a 25% CR replacement in the 0.33 w/b series led to approximately 50% and 36% increases in initial and final setting times, respectively. This setting time extension was more pronounced at higher w/b ratios.
- Compressive strength tests revealed that CR substitution significantly reduced the strength of SCM mixes compared to plain mortar. The rate of compressive strength reduction increased with higher CR replacement levels. Despite this, the rubber-modified SCM mixes achieved compressive strengths of at least 44 MPa.
- Statistical evaluation, including PCA, confirmed that CR replacement level and w/b ratio significantly influence fresh-state and strength characteristics. The CR replacement level was identified as the most dominant factor in determining these properties, while the w/b ratio had a comparatively minor influence on fresh characteristics and compressive strength. A strong and significant relationship among the experimental parameters and results further validated the reliability and consistency of the study.
- The findings suggest that CR-modified mortar can be effectively utilized in construction applications requiring specific rubber-modified mortar qualities, such as flowable fill-in subbase layers and specific highway applications. Such utilization would significantly contribute to reducing the disposal of used tires.

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Conflict of interest

The authors declare no conflict of interest.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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Author's contributions

Navvar Makansi: Formal analysis, Investigation, Resources, Writing - Original Draft; Süleyman İpek: Conceptualization, Validation, Formal analysis, Writing - Original Draft, Visualization; Erhan Güneyisi: Methodology, Writing - Review & Editing, Supervision, Project administration.

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