RESEARCH ARTICLE

Gravimetric weight loss of steel in self-compacting concrete blended with wood ash and silica fume

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Abstract

The present research work deals with the development of self-compacting concrete (SCC) containing wood ash (WA), silica fume (SF) and their combination (1:1 ratio). Several research studies have reported on the performance of WA and SF-blended SCC. However, very limited information is available on the effects of silica dioxide (SiO_2) and subsequent formation of calcium-silicate-hydrate (C-S–H) gel and its benefit on the strength and durability enhancement of self-compacting concrete. In this work, wood ash (WA) and silica fume (SF) were used as cement replacement materials, and studies were carried out on the chemical composition and its contribution in the strength development of SCC. Compressive strength, ultrasonic pulse velocity and dynamic modulus of elasticity have been increased when the cement is replaced with WA, SF and WA + SF content up to 10%, 6% and 30 + 8% respectively than normal SCC. From the EDAX analysis, Ca content in the mixes, NSCC mix has higher Ca content (52.04%) whereas 10% WA SCC, 6% SF and 30% WA + 6% SF SCC has 41.78%, 33.64% and 28.77% respectively. Similarly, SiO_2 content 6% SF-blended SCC has higher value (38.03%) than other mixes. As 6% SF-blended SCC has a higher value of SiO_2, it gives the higher compressive strength and UPV values because of high reactivity and subsequent formation of C-S–H gel.

Keywords Self-compacting concrete (SCC) · Calcium silicate hydrate (C-S–H) · Silica dioxide (SiO_2) · EDAX analysis · Wood ash (WA) · Silica fume (SF)

Introduction

Wood ash (WA) is an outcome of burning the fire wood/wood scrape from wood manufacturing company, and it is polluting the environment by means of airborne in smoke. In the burning process, majority of the harmful elements such as cellulose, carbon and lignin are removed leaving behind silica ash, which is essential to react with the cement (Cheah and Ramli 2011). The better-quality wood ash for cement replacement is achieved in terms of burning it by controlled temperature. The specific gravity, the silica formation and the fineness of the wood ash are mainly based

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on the controlled burning using the hot air oven/other heating chambers. Normally, the burning temperature is maintaining from 500 to 800 °C to incinerating the wood/wood scrapes. The amount of reactivity of WA is based on the amorphous silica content presented in the ash. However, it is purely based on the fineness of the WA (Raheem and Ige 2019; Ramos 2013; Ramos et al. 2013). So, before using WA as a cement replacing material, it must be ground well to achieve the desired fineness. The production of wood ash is primarily in areas where wood is used as coals for boiler that are abundant (Chowdhury et al. 2015). Based on the impurities and the burning conditions, the color of the WA varies from gray or half white. The WA remains unreactive when burnt in unrestrained combustion, as a result of which there are changes in the mineralogical composition (Akinyemi Banjo Ayobami 2021). Silica content in WA is crystalline in nature with respect to the burning and environmental condition (Sigvardsen et al. 2020). Cristobalite and tridymite forms of unreactive silica are retained in large portions, and it should be ground more finely to increase the pozzolanic activity (Temitope Funmilayo et. al, Meko and

Ighalo 2021). Calcium silicate hydrates formed due to the presence of silica with available lime are mainly responsible for the strength aspects in concrete. When WA is burnt between 550 and 700 °C, amorphous silica is produced; when temperature is increased further to 900 °C, the formation of unwanted crystalline occurs. For better and good strength aspects, 800 °C is to be maintained for a period of 12 h (Akinyemi and Dai 2020).

Silica fume (SF) is also an effective pozzolanic material used to replace the ordinary Portland cement (OPC) (HesamMadani and Norouzifar 2018). It is obtained from the alloy industries. While increasing the temperature up to 1800 to 2100 °C, developing the silicon dioxide vapour and cooling it, suddenly the SF is produced (Benli et al. 2017). SF particles are finer than all other pozzolanic materials such as fly ash, rice husk ash and metakaolin, and it has spherical in shape having a mean size of 0.05–0.3 μm. The fine particle size of the SF makes the concrete mix complicated to handle, from a practical perspective (Liu et al. 2021). It is mainly because of the high reactivity of the SF with water in the concrete mix (Benaicha et al. 2015). In order to make ease handling, either water-cement ratio may be increased or suitable amount of the chemical admixture can be added as a water-reducing agent. The addition of SF in concrete mix will lead to the early age strength, low permeability of water and increase in the durability of the concrete and electrical resistivity (Ardalan et al. 2017) (Ghoddousi and Saadabadi 2017).

Four parameters such as water binder ratio, binder segregate ratio, mix proportion of the concrete materials and degree of consolidation are mainly responsible for the variations in compressive strength (Flores Medina et al. 2015; Singh et al. 2021).

Nondestructive technique is used to indicate the strength and the damage level in a structure. IS 13311 part 1 is used as a reference to identify the physical as well the dynamic elasticity modulus quality of concrete using ultrasonic pulse testing technique. The ultrasonic pulse velocity of SCC is found to be much higher than that of the controlled concrete due to the formation of the dense pore structure when seen using SEM analysis. As very few literatures have been done on this area, this research work is carried out to understand the behaviour in detail.

Materials and methods

Materials

Ordinary Portland cement (OPC) of 43 grades, following the Indian Standard code IS 8112–1989, was used. Well-graded river sand passed through 4.75-mm sieve with a fineness modulus of 2.79 and a specific gravity of 2.48 (conforming to IS 383–1970) was used in the SCC. Locally available crushed granite aggregate, passing through 20-mm and 12.5-mm sieve while being retained on 4.75-mm sieve with a fineness modulus of 6.32 and a specific gravity of 2.73 (which is conforming to IS 383–1970), was used as a coarse aggregate. Wood scrap was collected from a wood saw mill, situated in Tirunelveli area. Firstly, the wood scrap is fired in uncontrolled manner. The uncontrolled fired wood ash is black in colour due to an excess amount of carbon content. The finely ground uncontrolled mill-fired black wood ash residue powders were again burnt in an industrial furnace at a temperature of 700 °C over a period of 30 min to prepare reburnt ashes as described below:

Black wood ash residue powder was prepared from the saw mill waste, and it was placed in the furnace for further thermal treatments. The rate of temperature rise was maintained at the rate of 200 °C per hour; further, it was continued where the temperature reached the desired heat of 700 °C over a period of 30 min. When the temperature maintained at 700 °C, all the carbon contents were burnt and turned to reactive silica. During this process, the un-burnt carbon present in this ash was removed. The wood ash was pulverized before it was used as a cement replacement material. This wood ash obtained by controlled re-burning processes was termed as simply wood ash (WA) and was used throughout the present investigation. Commercial-available silica fume with mean grain size of 0.05–0.2 μm and 89.2% of silica contents were used for this work. The physical and chemical properties of wood ash and silica fume are presented in proceeding sections. High range water reducer (Conplast SP430) was used as the superplasticizer (SP). It is based on sulphonated napthalene polymers and is supplied as a brown liquid instantly dispersible in water. It has been specially formulated to give high water reductions without loss of workability or to produce high-quality concrete of reduced permeability. It complies with IS 9103:1999 and BS 5075 Part 3 and ASTM-C-494 Type 'F' as a high range water-reducing (HRWR) admixture.

Methods

The particle size distribution (PSD) for OPC, WA and SF is performed using Nanotrac 10.5.2, and X-ray diffraction (XRD) for all the materials is performed with continuous scan type and PSD mode of scanning.

A total of seventeen different proportions of SCC mixes with WA and SF (WA ranging from 5, 10, 15… 30%, SF ranging from 2, 4, 6 …0.12% and WA + SF ranging from 10 + 2, 20 + 4, 30 + 6 and 40 + 8% by the mass of cement), including one normal SCC mix, were prepared with water to binder, W / (C + B) ratio of 0.50 and 2% of SP for a design cube compressive strength of 37.2 MPa. These mixes were designated as CSCC for normal self-compacting concrete,

WA1 to WA6 for WA-blended SCC, SF1 to SF6 for SF-blended SCC and WS1 to WS4 for WA in combination with SF-blended SCC. The mix proportions are summarized in Tables 1 (for binary mix) and 2 (for ternary mix).

During the production of SCC, the mixing order is important to obtain homogeneity and uniformity in all mixtures. Initially, the batching process is carried out, and all the materials were separately placed on a nonporous plate. Mixing sequences consisting of Fa and Ca are mixed for 30 s in the laboratory mixing machine to achieve homogeneity, and then, about 50% of the mixing water is added to the mixer machine, and mixing is continued for one more minute. Thereafter, the mixing process is stopped to allow the aggregates to absorb the water for 1 min. Before adding the cement and admixtures (WA or SF or WA + SF), they are mixed in the dry state, then added to the mixing drum. Finally, the SP is poured in the remaining water and introduced to the mixture, and mixing is restarted for 5 min. The mixed concrete is assessed to check its fresh state properties and then placed in the required moulds for curing. For all the mixes, six cube specimens of 150-mm size were prepared from each mix to check the compressive strength of various mixes. Compressive strength of the binary and ternary blended SCC

cubes was determined after 7 and 28 days of water curing as per IS 516–1956.

The test for ultrasonic pulse velocity of the binary and ternary blended SCC was carried out in accordance with IS 13311 Part 1 (1992). The operational stage of the ultrasonic pulse velocity test is shown in Fig. 1. The test was conducted at the age of 28 days. Triplicate 100-mm cubes were tested at the age. The specimens were air-dried at room temperature (23 ± 20 °C) for 24 h prior to testing. The drying process helped to obtain good coupling between the transducers and the specimens. The average path length of the specimens was determined by taking the measurement at four quaternary longitudinal locations. A ROOP Telsonic Ultrasonix portable ultrasonic nondestructive digital indicating tester (UX 4600) was used for determining the ultrasonic pulse velocity. The apparatus was used only when the transducers were zeroed by placing them face to face with water-soluble coupling gel. During the testing, the transducers were coupled firmly to the specimen ends and the transit time was recorded. The ultrasonic pulse velocity (V) was determined from measured transit time (T) and path length (L) and averaged based on the results of three specimens as follows:

Table 1 Mix proportion of binary blended SCC

Binary blended SCC mix designation	WA or SF (%)	Quantities (kg/m³)					
		Water	Cement	WA or SF	SP	Fa	Ca
CSCC	0	190	380	0	7.6	836	760
WA1	5	190	361	19	7.6	836	760
WA2	10	190	342	38	7.6	836	760
WA3	15	190	323	57	7.6	836	760
WA4	20	190	304	76	7.6	836	760
WA5	25	190	285	95	7.6	836	760
WA6	30	190	266	114	7.6	836	760
SF1	2	190	372.4	7.6	7.6	836	760
SF2	4	190	364.8	15.2	7.6	836	760
SF3	6	190	357.2	22.8	7.6	836	760
SF4	8	190	349.6	30.4	7.6	836	760
SF5	10	190	342	38	7.6	836	760
SF6	12	190	334.4	45.6	7.6	836	760

Table 2 Mix proportion of ternary blended SCC

Ternary blended SCC mix designation	WA + SF (%)	Quantities (kg/m³)					
		Water	Cement	WA + SF	SP	Fa	Ca
WS1	10 + 2	190	334.4	38 + 7.6	7.6	836	760
WS2	20 + 4	190	288.8	76 + 15.2	7.6	836	760
WS3	30 + 6	190	243.2	114 + 22.8	7.6	836	760
WS4	40 + 8	190	197.6	152 + 30.4	7.6	836	760

Water to binder ratio W/(B) = 0.5

Fa fine aggregate, *Ca* coarse aggregate

Fig. 1 Test setup for USPV and dynamic modulus of elasticity specimen
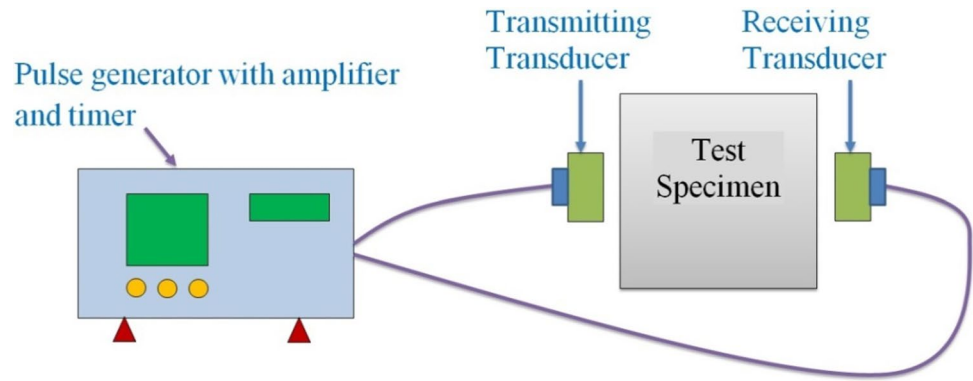
$$V = \frac{T}{L} \qquad (1)$$

The test for dynamic modulus of elasticity of the binary and ternary blended SCC was also carried out in accordance with IS13311 Part 1 (1992). The dynamic modulus of elasticity (E_d) of SCC may be determined from the ultrasonic pulse velocity (V) and dynamic Poisson's ratio (μ), using the following relationship,

$$E_d = \frac{\rho(1 + \mu)(1 - 2\mu)}{(1 - \mu)} \times V^2 \qquad (2)$$

where

E_d dynamic modulus of elasticity.

ρ density of SCC in kg/m.^{3}

μ dynamic Poisson's ratio (0.2–0.35).

V pulse velocity in m/s.

The value of the dynamic Poisson's ratio varies from 0.20 to 0.35; for this work, the dynamic Poisson's ratio was taken as 0.24.

In this work, gravimetric weight loss method was used to check the probable corrosion rate. The main advantage of using this method is to get the overall corrosion rate of the concrete during the total exposure time. For this corrosion test, three concrete cube specimens of 100 mm were prepared from each mix (NSCC, WA, SF and WA + SF-blended SCC). And a 12-mm round bar with 50-mm length was inserted at one of the corners with 25-mm cover thickness. Before starting the test, the steel bars were cleaned with hydrochloric acid and washed with distilled water. The initial weight of the steel bar was taken before inserting into the concrete. The gravimetric weight loss method was adopted as per ASTM G1-90.

All the specimens were immersed in to the 3% NaCl solution after 28-day water curing. The same condition were maintained for a period of 15 days and then subjected to 15-day drying. Fifteen days of wet condition and 15 days of dry condition were considered as one cycle. Similarly, a total of 18 cycles were used, and the weight loss (corrosion rate) was calculated by the following expression.

$$\text{Corrosion rate (mmpy)} = \frac{87.6 \times W}{DAt} \qquad (3)$$

where

W weight loss (mg).

D density of the material used (g/cm^3).

A the surface area of the specimen (cm^2).

t the time duration in (h).

For the complete assessment of corrosion resistance performance of steel bar in WA, SF-blended SCC, the percentage reduction in corrosion rate (CR) was estimated by the following expression.

$$\text{Percentage reduction in CR} = \frac{CR - CR_{(WA/SF/WA+SF)}}{CR} \qquad (4)$$

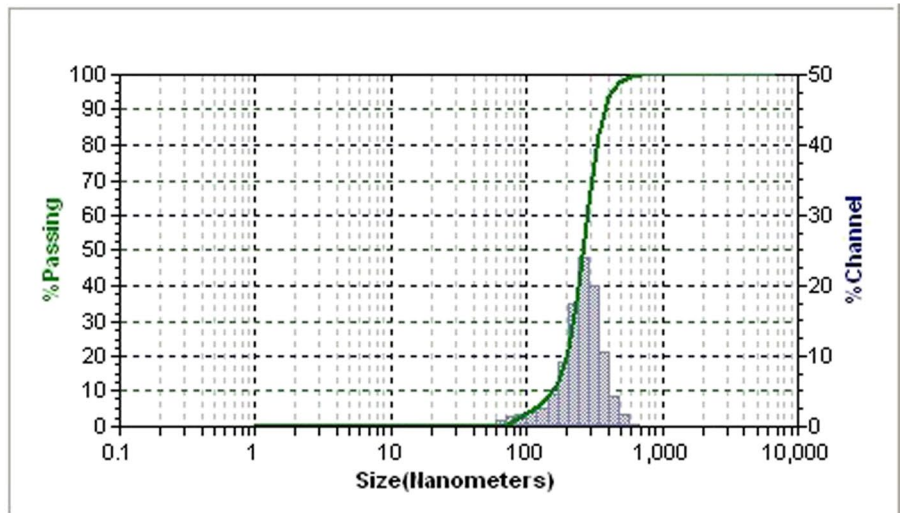where CR and CR$_{(ash)}$ are the corrosion rate values in the absence and presence of ashes respectively.
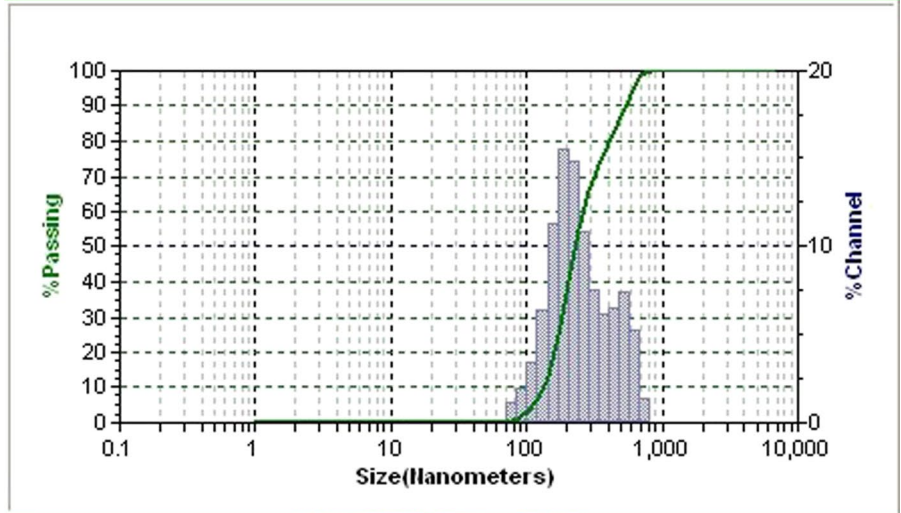
Result and discussion

Physical and chemical analysis of OPC, WA and SF

The particle size distribution for OPC, WA and SF is shown in Fig. 2. From Fig. 2, the OPC particle size varies from
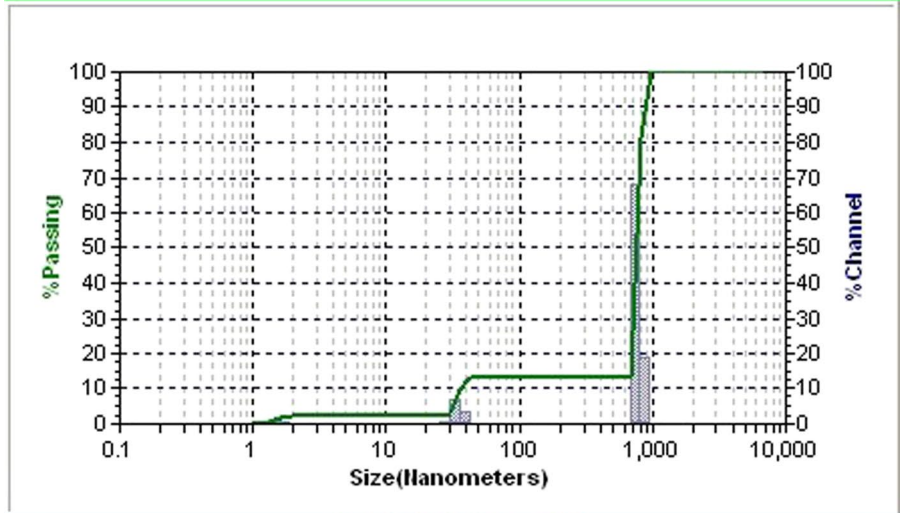
Fig. 2 Particle size distribution for OPC, WA and SF

(a) PSD for OPC

(b) PSD for WA

(c) PSD for SF

200 to 700 nm and the WA particle size varies from 100 to 300 nm (Batayneh et al. 2007). But, in the case of SF, the particle size is varying from 700 to 900 nm, and showing the very fine particle than other materials like OPC and WA. The WA particle size is not uniform like OPC and SF, and coarse structure is presented. However, it has the required particle size for blending with the OPC and SF during the mixing process. The XRD for OPC, WA and SF is presented in Fig. 3. From the XRD analysis, the WA and SF contain major quantity of silica than other cementitious chemical components. It indicated the possibility of enhancing the structural properties of the concrete during the hardening process. Also, it will lead to the formation of C-S-H and subsequent strength and durability property improvement.

The physical characteristics of OPC, WA and SF such as fineness, particle shape and size, density and colour were evaluated (Akinremi and Dai 2020). The physical properties of these SCMs appear to have greater influence on the performance of fresh and harden SCC relating to workability, bleeding, segregation and setting time, strength, etc. The measurement of fineness has attracted a great deal of attention, but we can observe the controversy again. The most commonly used sieve is around 75 μm, although this measure of fineness has its shortcomings. This is simple, sensible, reliable and cheap and has been found to be useful in identifying the overall quality of WA and SF for the cement replacement purposes. The fineness (percentage of passing of sieve 75 μm) of OPC, WA and SF measured by 75-μm sieve is found to be 86%, 89% and 99% respectively (Table 3).

The measurement of fineness for WA and SF is measured (specific surface area) by Blaine's air permeability method, which is accepted in Portland cement industry and is favoured for WA and SF (Karthiga et al. 2022a, b). It is also proved to be a reliable method. The specific surface area of very fine ashes is predominantly controlled by the micropores, and the factors influencing specific surface area can be best studied using BET's analysis. The particle size of WA would have significance on specific surface area measured by BET's analysis since these particles are similar to the average micropore diameter. The specific surface area of OPC, WA and SF determined by using Blaine's air permeability is shown in Table 3. In addition, the specific area of WA is studied using BET's nitrogen adsorption method, and the values are also presented in Table 3. The average specific surface area of WA is found to be 415 m^2/g (Blaine's), and the OPC and SF have an average specific surface area of 318 m^2/kg (Blaine's) and 16,580 m^2/kg (Blaine's) respectively (Shehata and Thomas 2002). The specific surface area of WA and SF, measured by Blaine's and BET's fineness, is found to be higher than that of OPC. However, the specific surface area of SF is found to be higher than that of OPC and WA. According to the earlier investigations, neither the

standard Blaine's air permeability method/BET's method by nitrogen adsorption nor the residues on 75-μm sieve were found to provide a good indication of complete particle size distribution. It may lead to the introduction of the concept of grading by particle size distribution curves.

The other physical properties of OPC, WA and SF are compared and reported in Table 3. The density, specific gravity and mean particle size of WA and SF are found to be lower than those of OPC. The density of WA and SF depends on the constituents (silica, alumina, iron oxide and alkalis), and higher carbon contents tend to lower the density. The WA material is very porous, which explains that it has a high specific surface area, and like those of cement, the particles of WA are irregular cellular. The carbon is intimately disbursed in the amorphous silica structure.

Compressive strength of SCC

WA and SF-replaced concrete samples were tested for compressive strength for 7, 28 and 90 days as shown in Figs. 4, 5 and 6 respectively. There was increase in compressive strength when binary materials for about 6–10% were replaced in SCC at 28 and 90 days. The same increases in strength were not found when ternary materials were used in SCC, i.e., WA + SF at 90 days, but for 28 days were found to be higher. The values of 28-day compressive strength for 10% WA and 6% SF were about 46.94 and 59.91 MPa respectively. The value of compressive strength was 59.9 MPa when 30% of WA + 69% of SF was used in SCC.

It is also observed that the equivalent or higher values of compressive strength of binary and ternary blended SCC at 28 days are obtained at 25% WA and 30% SF in the case of the binary system. But in the case of the ternary blended SCC, it is obtained at 40% of WA + SF (20% WA + 20% SF). Therefore, 25% WA, 30% SF and 40% WA + SF are considered the optimal limit. When 10% WA was used, there was increase in compressive strength when compared with the controlled concrete relevant to Sashidhar and Rao (2010) and Raheem and Adenuga (2013), due to the presence of silica content in the amorphous state which is mainly responsible for the pozzolanic activity. The compressive strength for SCC with 6% SF at 7 days was found to be 43.67 MPa when experimentally tested, and it was found to be greater than the 90-day compressive strength (41.6 MPa) of controlled concrete. The compressive strength of SCC was 40.54, 38.97 and 54.79 MPa when 30% of WA and 6% of SF were used as ternary systems at 7, 28 and 90 days respectively which was similar to the previous works. The increase in the compressive strength relatively is shown in Fig. 5 for 10% WA, 6% SF and 30% WA and 6% SF for 7, 28 and 90 days. When 6% SF was used, the relative increase in the compressive strength was found to have a minimal value of about 45.57% at 28 days, and further, it reduced at 90 days. When 30%
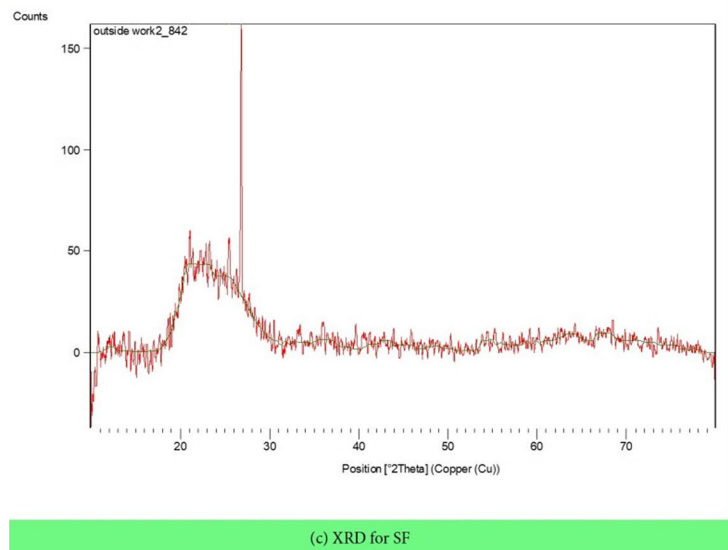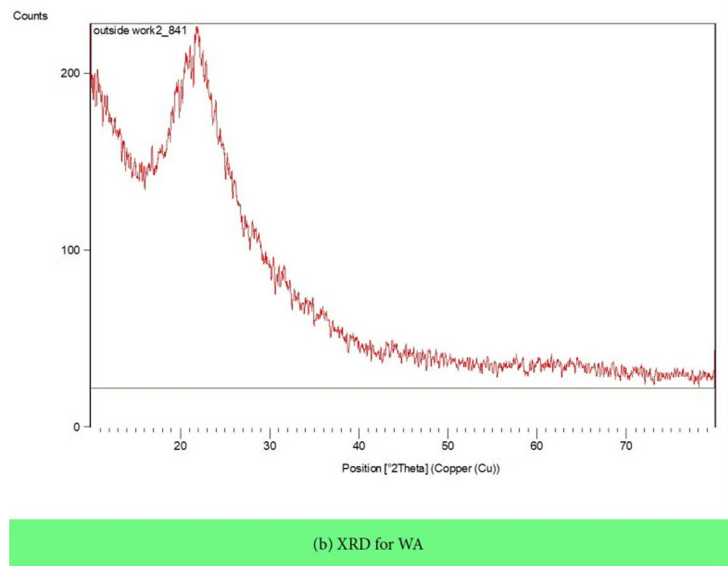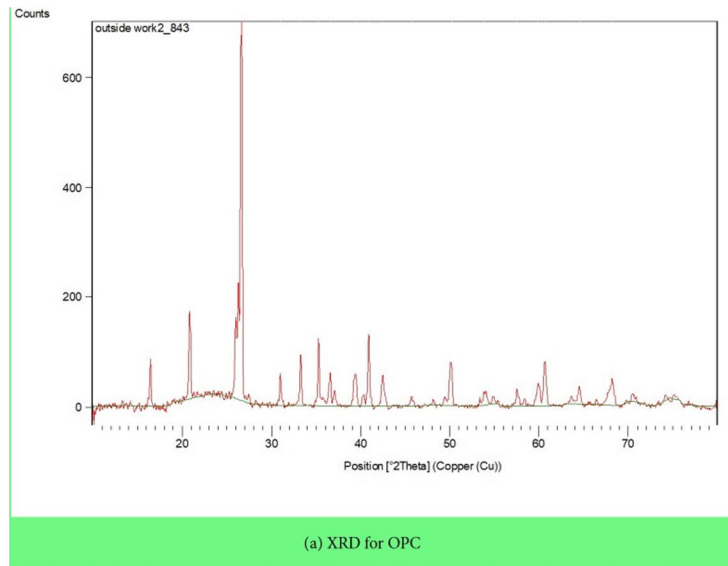
Fig. 3 XRD for OPC, WA and SF

(a) XRD for OPC

(b) XRD for WA

(c) XRD for SF

Table 3 Physical properties of OPC, WA and SF

Materials	Bulk density (g/cm³)		Specific gravity	Fineness passing 75-μ sieve	Specific surface (Blaine's) (m²/kg)	Mean particle size (μm)	Specific surface (BET's) (m²/g)
	Loose	Dense					
OPC	1.21	1.29	3.13	86	318	23.4	-
WA	0.42	0.54	2.03	89	415	21.7	0.432
SF	0.51	0.54	2.49	99	16,580	0.18	18.48
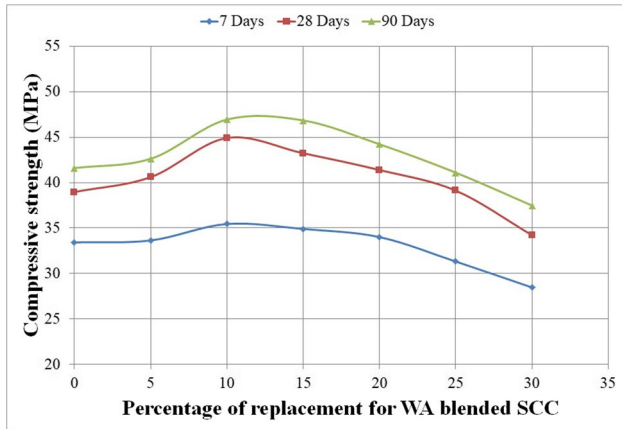
Fig. 4 Compressive strength of WA-blended SCC
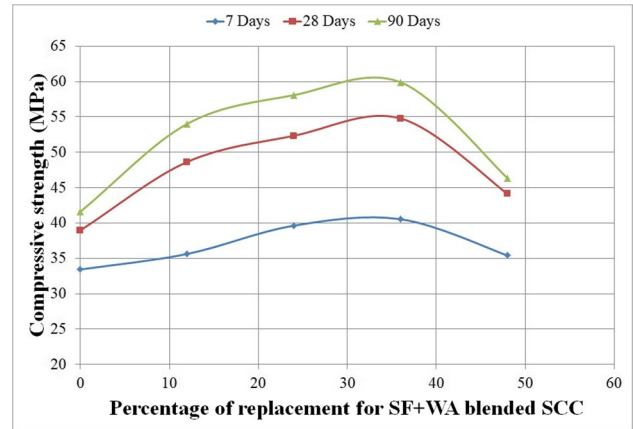

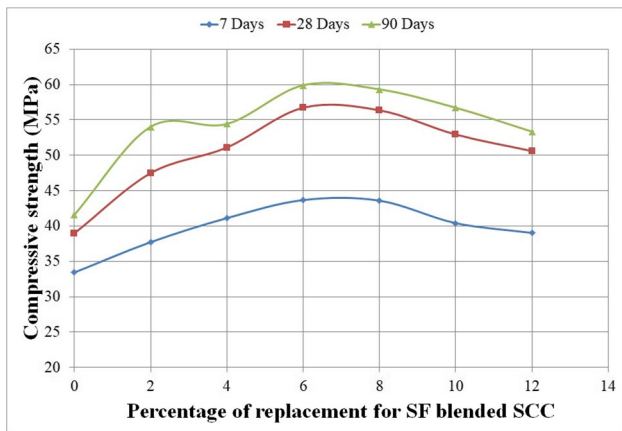**Fig. 6** Compressive strength of WA + SF-blended SCC

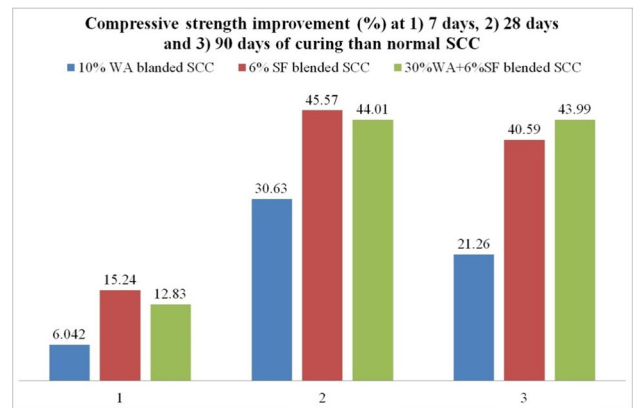**Fig. 5** Compressive strength of SF-blended SCC

Fig. 7 Relative increase in compressive strength of 10% WA, 6% SF and 30% WA + 6% SF-blended SCC

WA and 6% SF was used, the relative compressive strength attained a maximum value of about 40.59% and it confirms to the fact that early compressive strength was attained similar to the result when 6% SF was used in SCC.

Thus, the reasons for the early compressive strength development of SF and WA + SF-blended SCC and increase in the compressive strength up to 6% and 30% + 6% cement replacement of SF and WA + SF may be due to the chemical composition, silica content, fineness, amorphous phase, specific surface area and degree of reactivity of SF and WA. It

may also be due to the pozzolanic reaction between calcium hydroxide and reactive silica in SF and WA in the alkaline environment as reported by previous authors.

Ultrasonic pulse velocity

The UPV values were measured experimentally for WA and SF-blended concrete, and it is shown in Figs. 7, 8 and 9. The variation in UPV values for various mixes (WA and SF-blended SCC) shows the similar trend in the compressive
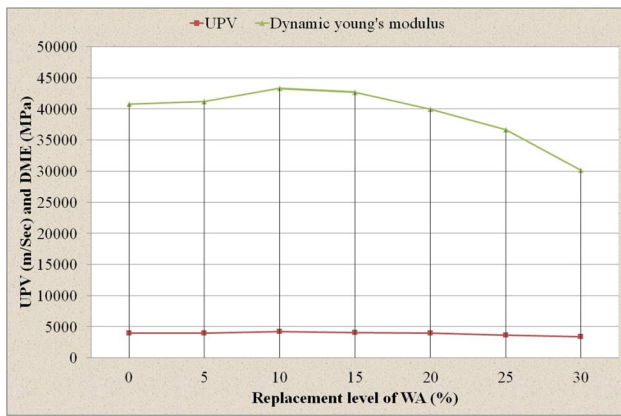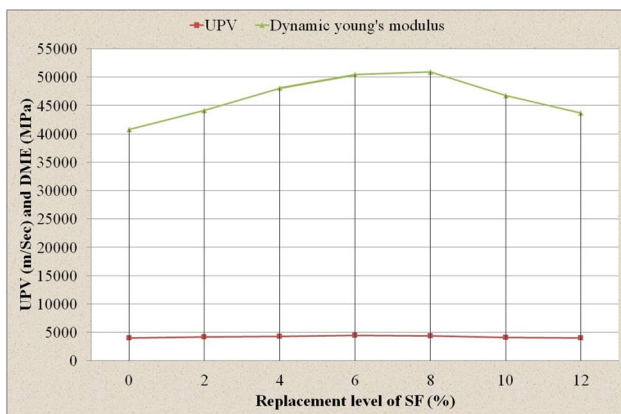
Fig. 8 UPV and DME for WA-blended SCC

Fig. 9 UPV and DME for SF-blended SCC

strength development in various mixes. As expected, the UPV value of blended SCC increases with the increasing of replacement level up to 10% WA, 6% SF and 30% WA + 6% SF then decreases, but the equivalent or higher UPV values of the unblended SCC are obtained at 15% WA, 12% SF and 40% WA + 8% SF. From the DME improvement in the WA, SF replacement shows the beneficial use of ternary system in OPC up to 48%. The UPV value of blended SCC has been found to be higher than the unblended SCC for some extent of replacement level of cement by WA, SF and their combination at 28 days. The reason may be due to the high rate of hydration, and lower porosity due to its higher surface area of a particular material.

Forty percent WA + 8% SF replacement was found to be optimal, and UPV was used to find the properties of materials that are used in concreting. It was found that UPV gets increased as the internal structure is found denser and in turn increases the compressive strength. At the initial stages, the grain rate is found to be higher which increases the UPV grain rate, also when SF is used as replacement. Binary blended SCC with WA + SF was used as replacement value

of UPV that is improved until 6% SF. In case of ternary blended SCC, nearly 48% replacement of cement was done using WA + SF and the results were found to be good due to the increased pozzolanic reaction. Thirty percent WA + 6% SF gave good results in UPV also. Binary and ternary mixes that fall under the category of very good in UPV testing were found to be WA4, WA5 and WA6. It all implies the beneficiary effect of WA and SF in the binary and ternary blended systems on the mechanical property (UPV and DME).

Dynamic modulus of elasticity

The dynamic modulus of elasticity values predicted from the ultrasonic pulse velocity (UPV) of concrete specimens is found to be more important than that of the static method because of the static testing if obtained from NDT and it does not signify the elastic behaviour of concrete directly, whereas dynamic modulus testing from UPV is not affected by creep.

The dynamic modulus of elasticity (DME) values calculated for WA, SF and their combination blended SCC specimens are also presented in Figs. 7, 8 and 9. As expected, DME increased with an increasing percentage of WA up to 10%, SF up to 6% and of the combination of WA and SF up to 30% + 6%. The DME behaviour of SCC containing WA and SF is very similar to the other mechanical properties like compressive strength and UPV. When considering all mixtures, the DME values are higher than those of the NSCC (100% OPC) except 20%, 25% and 30% of WA-blended SCC. The higher DME value was observed in 6% of the SF-blended SCC. Therefore, 15% WA, 12% SF and 40% WA + 12% SF are considered an optimal limit. Some researches have stated that the DME values are always closer to compressive strength and UPV values. From several properties in concrete, the modulus of the elasticity of concrete is one of the important properties for the assessment of structural behaviour, and it is used as an input parameter for the structural analyses.

Scanning electron microscopy (SEM) with EDAX analysis

SEM images for the various proportions of concrete with 10% WA, 6% SF and 30% WA + 6% SF are shown in Fig. 10. From the SEM images, it was concluded that micropores of irregular shape were found in unblended concrete and this was the main reason for the poor performance in the mechanical strength as shown in Fig. 10a. SEM images as shown in Fig. 10b−d explain that the samples are nonporous because of the occurrence of hydration process due to the presence of WA and SF (Cheah et al. 2020) as in turn reduces the pore structure to a greater effect when compared to the controlled concrete. The formation of ettringite
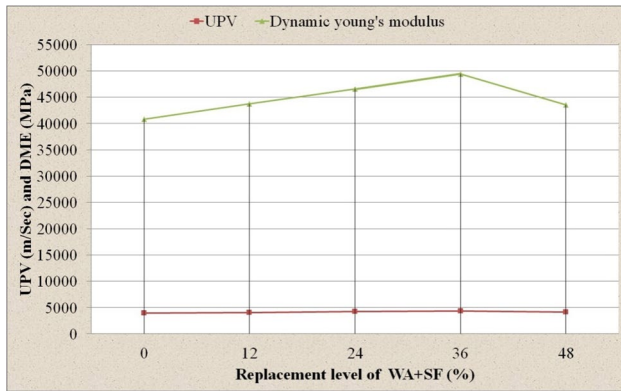
Fig. 10 UPV and DME for WA + SF-blended SCC

is shown as a needle-like crystalline structure for unblended concrete of SCC, and it is reduced due to the pozzolanic reactions of WA and SF as shown in Fig. 10d.

Effects of SiO$_2$ on strength improvement

In order to study the impact of SiO$_2$ content in the strength development of SCC blends with WA and SF, energy-dispersive spectroscopy (EDAX) analysis was carried out for NSCC (100% OPC), 10% WA-blended SCC, 6% SF-blended SCC and 30% WA + 6% SF-blended SCC. The results are presented in Fig. 11. From the EDAX spectrum analysis, calcium oxide (CaO) and silica dioxide (SiO$_2$) (Fig. 12)

contents are varying for different mixes. From previous studies and facts, both calcium oxide and silica dioxide have the predominant quantity responsible for the strength and the durability properties of any cement concrete. When looking on the Ca content in the mixes, NSCC mix has higher Ca content (52.04%) whereas 10% WA SCC, 6% SF and 30% WA + 6% SF SCC has 41.78%, 33.64% and 28.77% respectively. While considering of SiO$_2$ content, 6% SF-blended SCC has higher value (38.03%) than other mixes. As 6% SF-blended SCC has a higher value of SiO$_2$, it gives the higher compressive strength and UPV values due to the high reactivity and subsequent formation of C–S–H gel. Other elements such as Mg, Fe, Al and Cu are more or less equal to the NSCC. From this EDAX study, it can be concluded that the SiO$_2$ content is responsible for the higher strength without compromising the other element quantity requirements (Karthiga and Praveena 2022).

Gravimetric weight loss method

The corrosion rate of WA and SF-blended SCC for steel reinforcement embedded in SCC is presented in Table 4. For control self-compacting concrete (CSCC), the corrosion rate (CR) is found to be 20.13×10^{-3} mmpy. CR for WA, SF and WA + SF-blended SCC varies from 9.99 to 29.20 mmpy, 6.12 to 64.16 mmpy and 7.18 to 22.98 mmpy respectively. The lowest CR values were obtained in 15% WA, 6% SF and 36% WS-blended SCC. Steel embedded in 15% CRL with WA-blended SCC showed 2 times decrease in CR than

Fig. 11 Scanning electron microscopic (SEM) image of **a** un-blended SCC (100% OPC), **b** 10% WA-blended SCC, **c** 6% SF-blended SCC and **d** 30% WA + 6% SF-blended samples
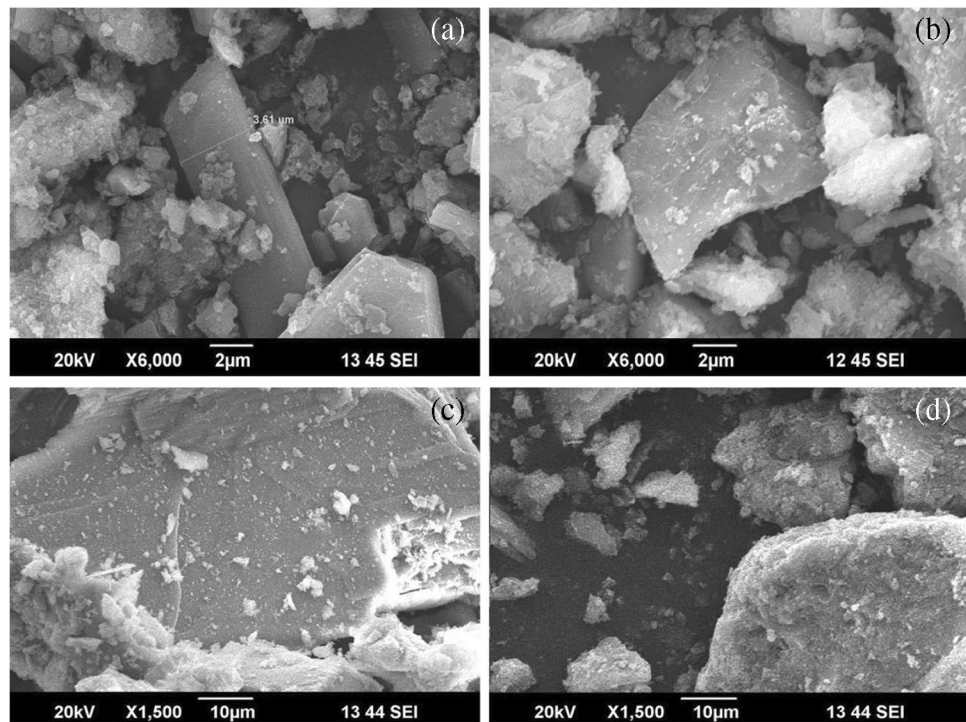
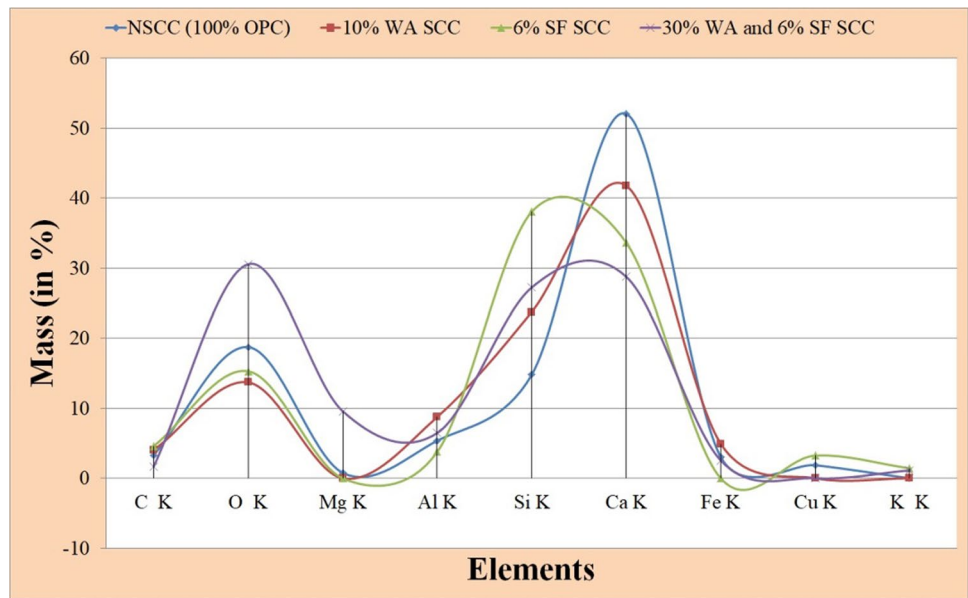**Fig. 12** EDAX results for NSCC, 10% WA, 6% SF and 30% WA + 6% SF-blended SCC

Table 4 Gravimetric method of corrosion rate of WA, SF and WA + SF blended SCC

Specimen	Cement replacement level % (WA/SF/ WA + SF)	Corrosion rate × 10^{-3} mmpy	Efficiency $\frac{CR - CR_{(R)}}{CR}$
CSCC	0	20.13	0
WA1	5	14.39	27.86
WA2	10	10.17	49.47
WA3	15	9.99	50.37
WA4	20	14.45	28.21
WA5	25	20.28	− 0.74
WA6	30	29.20	− 45.05
SF1	2	16.22	19.42
SF2	4	8.09	59.81
SF3	6	6.12	69.44
SF4	8	10.01	50.27
SF5	10	27.24	− 35.32
SF6	12	64.16	− 218.7
WS1	12	14.95	25.73
WS2	24	10.22	49.23
WS3	36	7.18	64.33
WS4	48	22.98	− 14.15

control self-compacting concrete. The percentage reduction in CR data reported for WA-blended SCC also revealed a maximum value of 50.37% at 15% CRL. When considering all the mixes, SF-blended SCC (6%) shows the lowest CR (6.12 mmpy) and corrosion resistance is improved up to 69.59% than the control mix. Similarly, the CR value for ternary blended SCC (WA + SF) was observed as 7.18 mmpy at 36% cement replacement level. These results indicate that the introduction of pozzolanic material such as WA and SF in blended SCC improves protection against chloride-induced corrosion of steel.

Conclusion

From this experimental works, the following conclusions may be drawn:

1. The studies were carried out to identify the optimal level of replacement of ordinary Portland cement (OPC) with wood ash (WA) or silica fume (SF) in binary and ternary systems. In the case of the WA-blended SCC, the compressive strength increases with SF up to 10%, and then at 6% SF, the compressive strength attains equivalent to that of normal SCC in both 28 and 90 days of curing.
2. Twelve percent replacements of SF with OPC are found to be the optimal limit for the SF-blended SCC. For the WA + SF-blended SCC, the compressive strength increases with WA + SF up to 36%, and then at 40% WA + SF, the compressive strength attains equivalent to that of normal SCC in both 28 and 90 days of curing.
3. Forty percent replacements of the WA + SF with OPC is found to be the optimal limit for the WA + SF-blended SCC.
4. SEM with EDAX analysis of WA and SF-blended SCC confirmed the formation of a new phase such as calcium silicate hydrate (C-S–H) gel as hydration product.
5. Hardening process is enhanced more due to the presence of excess amount of SiO_2 in SF than WA, as a result of which the early compressive strength at 7 days is attained for 6% SF replacement when compared to the 90-day controlled concrete of SCC.

6. In the future, this work will be extended to review statistical analysis and other corrosion studies to ensure/confirm the effectiveness of the usage of WA and SF in binary and ternary systems.

Author contribution Kannan V and Karthiga Shenbagam N equally contributed for this work.

Data availability All the necessary data are given in the paper in detail.

Declarations

Ethical approval This is the work done by me and the PG students; it is not published anywhere else by us.

Consent to participate All the authors of this paper have given their consent to participate and act as one of the authors.

Consent for publication I, the author, give my consent for the publication of identifiable details, which can include photograph(s) or case history and details within the text.

Conflict of interest The authors declare no competing interests.

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