SUSTAINABILITY AND MATERIALS ENGINEERING

Rice Husk Ash-Modified Ready-Mixed Concrete under Prolonged Agitation: A Critical Review of Fresh, Mechanical and Durability Performance

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Abstract

Rice Husk Ash (RHA) is a silica-rich supplementary cementitious material that is widely reported to enhance the later-age properties of concrete. In ready-mixed concrete (RMC), however, the material must be able to perform after continuous agitation in the truck drum for a certain period of time, during which the hydration process has already taken place and there is a further change in the material properties. This paper critically examines the literature regarding RHA modified concrete in regards to extended mixing, agitation and ready-mix transit periods. The reviewed studies can be categorized into three groups: studies on production of RHA; studies on characterisation and performance of RHA blending with conventional mixing and curing; and studies on RHA-free RMC with a prolonged mixing or transit time. Special focus is paid to the burning conditions and to the characterisation of the ash, to the workability preservation, to the rheology, to the interaction between the superplasticiser and the concrete, to the mechanical properties, to the concrete durability and microstructure. The evidence shows that the burning temperature, fineness of RHA, porosity and residual carbon have significant effect on water demand and admixture requirement and that the mixing time and revolution count affect the performance of RHA-blended cementitious systems. Independent ready-mix studies demonstrate mix-specific changes to fresh properties during transit, and superplasticiser retempering is able to restore slump. In addition, RHA enhances the strength and durability of products at later ages when the ash is well burnt and ground and the replacement level is suitable. But relatively little work follows RHA modified concrete from batching to realistic drum agitation, to hardened performance. Hence, the relationship between characteristics of ash, agitation history, superplasticiser management and transit time needs to be determined prior to any recommendation for ready-mix supply using RHA.

Keywords: prolonged agitation; ready-mixed concrete; rice husk ash; superplasticiser; workability

1 Introduction

One of the primary methods the concrete industry has found to decrease clinker usage and carbon emissions is through use of supplementary cementitious materials (SCMs) [1], [2]. Rice husk ash (RHA), which is obtained from rice husks, has received special attention as an SCM due to its high silica content and pozzolanic property. If ash has been produced correctly and applied at an appropriate replacement rate, it may be able to impact the development of strength, pore refinement and durability [3], [4], [5], [6]. Burning regime, fineness and carbon content of ash, however, are crucial to its performance [7], [8].

The majority of the RHA studies that were reviewed here (Table 1 and Table 2) were conducted on laboratory mixes cast immediately after mixing. This is not the case with ready-mixed concrete. The batching-to-discharge elapsed time and number of revolutions of the drum during this time period

are part of the concrete's history (ASTM C94/C94M-23 [12]). Extended agitation can alter the properties of the mix such as consistency, air content, and admixture performance, which will vary according to the characteristics of the mix and the type and content of admixture [9], [10]. Prasittisopin and Trejo [11] found that the blending time and revolution count did affect the properties of blended cements containing RHA but their investigation was conducted on cementitious materials and not on the actual truck mixes.

Literature on workability, strength, durability and microstructure of RHA concrete is vast [13], [5], [6] and there is also a body of evidence on prolonged transit, but it relates to other concretes and not to RHA concrete. This paper summarizes the existing literature related to RHA modified concrete with long stirring and ready mixed mixing duration. It deals with the production and characterisation of the ash, comparison with the Portland limestone cement (PLC), changes in the fresh state during agitation, contributions of superplasticisers and later, the mechanical, durability and microstructural performance. Direct evidence gathered from RHA-containing systems is separated from indirect evidence provided by other ready-mixed concretes and the intent is to determine if any additional testing is necessary before RHA-modified concrete can be considered for actual delivery in ready-mixed concrete.

2 Production and characterisation of rice husk ash

Rice husk is the by-product of the milling of rice grains. It contains a lot of silica and the ash is rich in silica when burned [5], [6]. How well the burning is carried out largely determines the quality of the ash. Thiedeitz et al. [14] compared RHA of a field producer with laboratory produced ash and Raheem and Bello [8] compared the ash from five Nigerian producers and their compositions and whether they fulfilled the requirement of ASTM C618-19 [15].

Burning regime. The quality of the ash depends on the duration and temperature of burning. Burning at approximately 400 to 1100 °C has been found to be effective to produce a reactive ash [6] and it may be amorphous or crystallized as a function of the burn temperature and time spent at burn temperature. Wang et al. [16] found that two-stage regime of 60 minutes at 300 °C followed by 120 minutes at 600 °C yielded ash with no sharp crystalline peaks in XRD and LOI of ~4.5%. Habeeb and Mahmud [17] burnt husk at a temperature of not more than 690 °C, and they found that the resulting ash was mostly amorphous, having a silica content of 88.3% and an LOI of 5.8%. Shawsh and David [18] incinerated husk at 600, 700 and 800 °C and found 700 °C to be the best of the three. Almutlaqah et al. [7] re-burnt an uncontrolled combustion ash (about 475 °C). The as-received ash contained a high amount of carbon (LOI 13.5%) and also had a considerable cristobalite crystalline content (about 60% amorphous and 38% cristobalite), while burning the ash at 800 °C for 6 hours increased the cristobalite crystalline content to 68%. All these studies indicate that burning at about 500–700 °C results in a predominantly amorphous ash, while burning at 800 °C results in more crystallisation. The two-stage burning also reduced the amount of potassium compared to that obtained from single-stage burning [16].

Grinding and fineness. Often, grinding is performed following burning to make the particles smaller. Wang et al. [16] found that the mean particle size reduced from 35.5 to 5.9 μm (the cement had a mean size of 13.8 μm), and the 28-day pozzolanic activity index increased from 92% to 114%. After 30 minutes of grinding, a specific surface area of 56 m^2/g is mentioned by Endale et al. [6]. Habeeb and Mahmud [17] ground their ash for 90, 180 and 360 minutes, respectively, which decreased the

mean particle size from 63.8 μm to 11.5 μm but increased the specific surface area only slightly, and they postulated that this was due to the microporous structure of their ash.

Characterisation tests. The oxide composition is obtained by X-ray fluorescence (XRF) [8] and it was found that five Nigerian ashes contained SiO_2 between 70.1 and 81.1% (only one of which matched the Class N requirements of ASTM C618-19). The amorphous silica is recognizable from a broad hump around 15 to 25° 2θ, whereas cristobalite or quartz yield sharp peaks [16], [7]. The unburnt carbon content is measured by the LOI test, particle morphology is determined by scanning electron microscopy (SEM), and particle-size distribution and specific surface area express the fineness. Both the strength activity index (ASTM C618-19) and isothermal calorimetry are used to assess reactivity, and untreated ash released 185.5 J/g in 100 hours, while a well-treated ash had a value of 232.6 J/g, and the control had 249.3 J/g in 100 hours [7]. These studies are summarised in Table 1, but none of them examined the ash in a ready-mix setting.

Table 1. Burning, processing and characterisation of RHA in selected studies.

Study	Burning conditions	Processing	Tests	Principal outcome
Wang *et al.* [16]	Box furnace, two stages: 300 then 600 °C	Ball mill, 5 to 30 min	XRD, EDX, SEM, LOI, activity	Amorphous ash, LOI about 4.5%; 28-day activity index 92 to 114%
Shawsh and David [18]	Muffle furnace at 600, 700 and 800 °C, 2 h	Cooled, ground 30 min	XRF, XRD, strength	SiO_2 84.9 to 93.3%, LOI 8.5 to 3.6%; 700 °C best
Almutlaqah *et al.* [7]	Re-burning of ash from uncontrolled combustion, 400 to 800 °C, 3 or 6 h	Vibratory disc mill; burn-then-grind vs grind-then-burn	XRF, XRD, LOI, SEM, calorimetry	Raw ash 60% amorphous, 38% cristobalite, LOI 13.5%; 800 °C/6 h gave 68% cristobalite
Raheem and Bello [8]	Not reported (five Nigerian producers)	As supplied	XRF, XRD, LOI	SiO_2 70.1 to 81.1%; one of five ashes met ASTM C618 Class N
Endale *et al.* [6]	Review: about 400 to 1100 °C	Grinding; about 56 m^2/g after 30 min (cited)	Review	Silica generally above 70%, in some cases up to 97%

Applications and replacement levels. RHA has been employed primarily as a partial cement replacement and the optimum level is typically low (Table 2; Figure 1). Habeeb and Mahmud [17] used ash from three different fineness grades to replace 5 to 20% of the cement in 40 MPa concrete. The 10% replacement gave the highest 28-day gains, of 22.2, 26.7 and 30.8% for the three grades, while the superplasticiser demand reached 2% for the finest ash at 20% replacement. Givi et al. [19] reported that strength was enhanced with replacement of up to 15% and 20% for ash of about 95 μm and ultrafine ash (about 5 μm), respectively, with the highest strength at 10% ultrafine ash. Adina et al. [20] determined that the use of 7% RHA had a 28-day strength that was approximately 25% higher than that of normal concrete; however, for more than 10% RHA, the strength gain stopped and the concrete became very dry. Shawsh and David [18] found that 7.5% of the 700 °C ash gave 44.7 N/mm^2 against 35.6 N/mm^2 for the control. Zareei et al. [13] obtained a 20% increase in compressive strength with 15% replacement of RHA in the mix of high strength concrete; Kanthe [21] in his study has observed that the most optimum result was obtained at 10% replacement of RHA along with the use of super plasticiser. At the mortar scale a fixed replacement is used, 10% by Wang et al. [16] and 20% by Almutlaqah et al. [7].

Table 2. Applications of RHA and replacement levels reported in selected studies.

Study	System	RHA replacement tested	Other findings
Habeeb and Mahmud [17]	40 MPa concrete; ash burnt at 690 °C or below, three fineness grades	5, 10, 15, 20%	Finer ash gave higher strength but needed more superplasticiser (2% at 20%)
Givi *et al.* [19]	Binary blended concrete; ash of about 5 and 95 μm	5, 10, 15, 20%	Finer ash lowered workability and water absorption
Adina *et al.* [20]	Normal concrete, Nigeria	2, 4, 7, 10, 12%	Mix very dry above 10%
Shawsh and David [18]	G-30 concrete, water-cement ratio 0.55; ash burnt at 600, 700, 800 °C	5, 7.5, 10, 12.5%	Ash burnt at 800 °C gave the weakest concrete
Al-Alwan *et al.* [22]	Concrete; water-cement ratios 0.3 to 0.7; curing 10 to 30 days	0, 7, 14%	Fine RHA improved strength and limited chloride penetration; high water-cement ratio adverse
Kanthe [21]	Concrete with superplasticiser	10 to 50%	Durability results (acid, sulphate) satisfactory
Zareei *et al.* [13]	High-strength concrete with 10% micro silica	Up to 25%	Strength and durability improved at moderate replacement
Kannan and Ganesan [23]	Self-compacting concrete, binary and ternary blends with metakaolin	5 to 30% (binary); 10 to 40% (ternary)	Lowest weight loss in magnesium sulfate at 10% RHA; binder C_3A content influenced sulfate and corrosion performance
Wang *et al.* [16]	Mortar, water-binder ratio 0.5	10%	Activity index rose as the ash was ground finer
Almutlaqah *et al.* [7]	Mortar strength activity test	20%	Untreated ash below the 75% threshold; burn-then-grind most effective

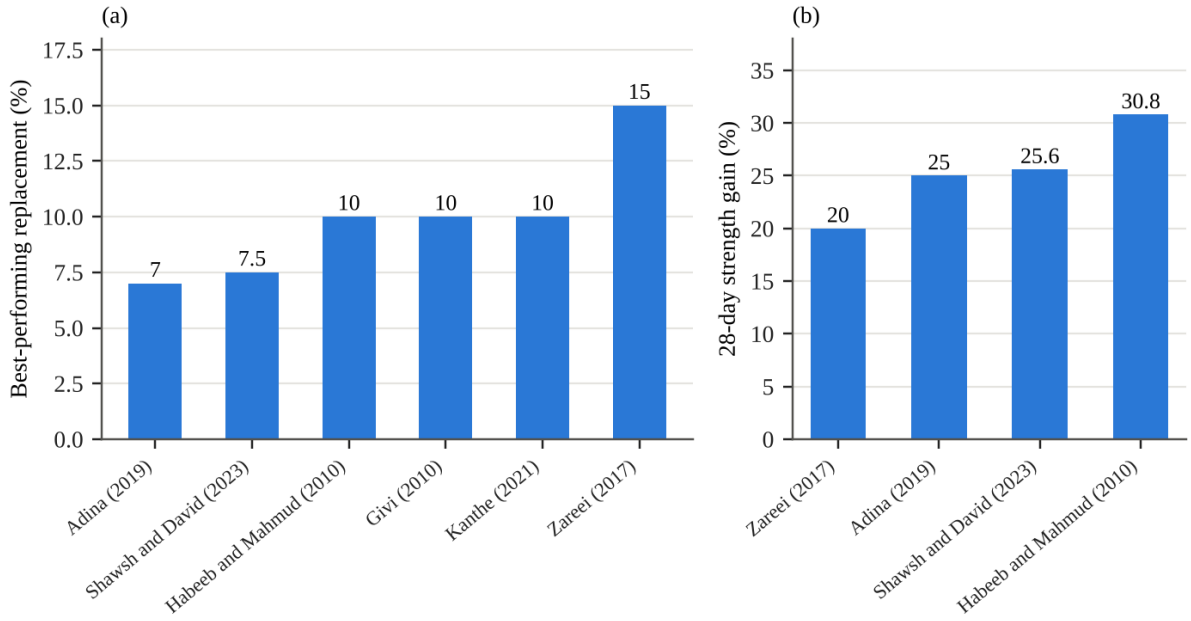


Figure 1. (a) Replacement level giving the best performance in the studies of Table 2, and (b) the 28-day strength gain over the control at that level.

The data plotted in Figure 1 are taken from [17], [19], [20], [18], [21] and [13]; the gains of Zareei et al. [13] and Adina et al. [20] are approximate, as reported.

On the whole, the levels that performed best are in the range of 7–15% of cement. Strength gains have been reported as continuing to be beneficial at levels up to approximately 15% [19] or with the addition of micro silica up to approximately 10% [13] but have been reported to level off or even decline above approximately 10% in some studies [17], [20]. These would be the most logical initial mixing levels for ready-mix mix designs, but there are no reports of studies examining prolonged agitation in these designs.

Properties of RHA compared with PLC. The chemical and physical properties are different between RHA and PLC. Here the reference binder is PLC because Portland limestone cements are the most used in Nigeria [24] and the use of them is specified in NIS 444-1. PLC is a blended cement in which limestone partly replaces clinker: EN 197-1 (2011) [27] allows 6 to 20% limestone in CEM II/A-L and 21 to 35% in CEM II/B-L, and ASTM C595/C595M-25 [26] allows 5 to 15% in Type IL. According to Danchuwa et al. [24] it has been reported in some researches as ordinary Portland cement, but in fact it is not a Portland cement as it contains less clinker. It has been determined that the addition of limestone does not negatively affect the pore structure as long as it is less than approximately 25% [25] though the strength begins to take a turn for the worse at about 15%. The silica content in RHA is much higher and the calcium oxide content is considerably lower as shown in Table 3, thus RHA cannot be used as a like-for-like cement replacement.

Table 3. Typical chemical and physical properties of RHA compared with PLC.

Property	RHA	PLC
SiO_2 (%)	70 to 97 (70.1 to 81.1 in five Nigerian ashes; 84.9 to 93.3 in [18])	20.6 in two Nigerian brands; NIS 444-1 range 18 to 24

Property	RHA	PLC
CaO (%)	Small [6]	60.8 to 62.7 in two Nigerian brands; NIS 444-1 range 59 to 67
Loss on ignition (%)	About 1 to 13.5 (unburnt carbon; higher for poorly burnt ash)	2.95 to 3.12 in two Nigerian brands; NIS 444-1 maximum 5.0
Limestone content (%)	Not applicable	6 to 35 (EN 197-1 [27]); 5 to 15 (ASTM C595/C595M Type IL)
Fineness	Mean size about 6 to 64 μm after grinding; about 56 m^2/g after 30 min grinding (cited by [6])	Residue on 90 μm sieve 31 and 42% in two Nigerian brands; 13.8 μm mean size for the cement of Wang *et al.* [16]
Silica phase	Largely amorphous at 600 to 700 °C or below; more cristobalite at 800 °C	Clinker phases plus limestone (EN 197-1)

Note: RHA values are compiled from the studies in Table 1 and from Endale et al. [6]; PLC values are those of Danchuwa et al. [24] for two Nigerian brands, with NIS 444-1 limits as quoted there. Specific gravity and PLC specific surface were not reported in the sources consulted.

3 Ready-mixed concrete and prolonged agitation

The drum is continually agitated and mixing times in the field can be much longer than those in the laboratory. ASTM C94/C94M-23 [12] specifies a 90 minute or 300 drum revolutions agitation period from the beginning of mixing unless otherwise specified by the purchaser and the producer. Olugboyega et al. [28] in their study of five RMC plants in Lagos State, Nigeria reported a mean time of 100 minutes between mixing and placing of concrete which exceeds that limit. The limit is not generally accepted: Mahgoub et al. [29] report that many trucks are rejected due to it and that approximately 3% of the total production volume is discarded as waste; they also state that they believe this limit is too conservative for the mixtures that they tested, based on tests carried out for 60 to 150 minutes.

The primary concern in the fresh state is workability lost in transit. Chakraborty et al. [10] used a 1:1.5:3 concrete containing water-cement ratio of 0.48 and produced in the drum at 18–20 rpm for a maximum of 210 minutes. The slump dropped from 210 mm to 30 mm without adding admixture, but with 1% of the Type B retarding admixture it stayed at 115 mm, and the 28-day compressive strength was not greatly influenced by the transit time (Figure 2). Erdoğdu et al. [30] reported that with the same initial slump, higher total cementitious content decreased slump loss in concrete made with fly ash and silica fume, while Bayer [9] reported complete loss of slump (no retempering) in 5 to 240 minutes for all seven mixes tested, which contained slag, fly ash, ground clay brick, and natural pozzolan. In three mixtures, Mahgoub et al. [29] stored the mixtures for 60 to 150 minutes, and they did not find any meaningful change in fresh or hardened properties, including resistivity and freeze-thaw resistance.

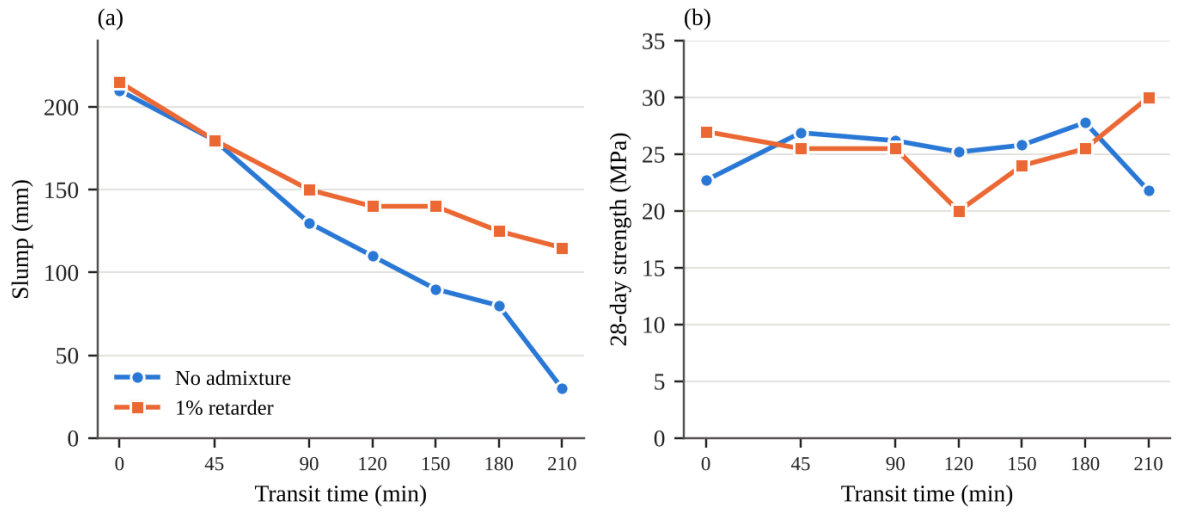


Figure 2. (a) Slump and (b) 28-day compressive strength of ready-mixed concrete sampled at different transit times, with and without 1% retarding admixture.

The data in Figure 2 are from Chakraborty et al. [10]; each strength value is the mean of three cylinders.

A large percentage of slump lost in transit can be regained on site through the use of water or an admixture (Table 4). Erdoğdu [31] reported that retempering with a Type F superplasticiser resulted in much higher 28-day strength than did retempering with water at all durations between 30 minutes and 150 minutes. Alhozaimy [32] analyzed 11 suppliers of ready-mixed concrete from 12 locations in a hot-dry climate, and found strength losses of below about 10% when the slump was kept at 100 ± 25 mm, and of up to 35% when the slump exceeded this range. Bayer [9] discovered that using superplasticiser retempering resulted in an increase of strength, without any loss of slump, although the air content decreased considerably. Thus, the extent and the method of retempering has an impact on the final hardened product as well as the fresh state. None of these studies included RHA, so they do not describe the behaviour of RHA mixtures, but they indicate the conditions that an RHA mixture would have to meet.

Table 4. Summary of key studies on prolonged agitation, retempering and mixing history.

Study	Material system	Variable investigated	Main findings as reported
Erdoğdu [31]	Concrete, initial slump about 19 cm	Mixing 30 to 150 min; retempering with Type F superplasticiser or water	Superplasticiser retempering gave higher 28-day strength than water
Erdoğdu *et al.* [30]	C25/30 concrete with fly ash and silica fume	Prolonged agitation; superplasticiser restoration	Higher total cementitious content reduced slump loss
Alhozaimy [32]	Ready-mixed concrete, 11 suppliers, hot-dry climate	Water added at site	Strength loss below 10% within 100 ± 25 mm slump; up to 35% beyond
Bayer [9]	Concretes with slag, fly ash, ground clay brick or natural pozzolan	Mixing 5 to 240 min; superplasticiser retempering	Slump fell to zero without retempering; air content fell with retempering; strengths rose slightly

Study	Material system	Variable investigated	Main findings as reported
Chakraborty *et al.* [10]	Ready-mixed concrete	Transit to 210 min; 1% retarder	Retarder reduced slump loss; 28-day strength not remarkably affected (Fig. 2)
Mahgoub *et al.* [29]	Three concrete mixtures	Discharge at 60 to 150 min	No meaningful change in fresh or hardened properties
Prasittisopin and Trejo [11]	RHA-blended cement	Mixing time and revolution count	Mixing history altered the characteristics of RHA blends
Msinjili *et al.* [33]	RHA-blended cementitious systems	Superplasticiser type and dosage	Type and dosage influenced rheology and early hydration

4 Results and discussion

The above sources enable the evidence related to RHA to be juxtaposed with the evidence related to ready-mix agitation. The time series of Chakraborty et al. [10] is the only complete one found for ready-mixed concrete (Figure 2). The slump decreased from 210 mm to 30 mm, an 86% loss of the initial slump value, without any admixture; with the retarder the slump decreased from 215 mm to 115 mm, a 47% loss of the initial value, but most of the difference occurred after 90 minutes. In contrast, the 28-day strengths fluctuated somewhat without admixture (21.8 to 27.8 MPa) and with the retarder (20.0 to 30.0 MPa) with no consistent decrease as a function of transit time. These figures should be treated with caution because the authors' abstract gives a final slump of 25 mm, whereas their table gives 30 mm.

4.1 Interaction between fresh properties, rheology and superplasticiser

The workability and rheology of fresh concrete can be significantly influenced by RHA, which is related to the fineness, porosity and replacement ratio of RHA and the amount of superplasticiser used [33], [34]. Habeeb and Mahmud [17] have found that the demand for superplasticiser increased with the finer ash while Givi et al. [19] have found that the workability declined with the finer ash but improved with coarser ash. There is not a single consistent result as the ash varies significantly from one study to another [5], [6]. Almutlaqah et al. [7] found that the as-received ash, with LOI of 13.5%, required a water-binder ratio of 0.71 while the control required a ratio of 0.48. Msinjili et al. [33] demonstrated that the type and dosage of superplasticiser have a significant impact on the rheology and early hydration of RHA blended systems, while Kanthe [21] investigated their influence on strength and durability of RHA concrete. There have also been correlations between rheology and strength with dosage for self-compacting concrete [35].

In the case of ready-mixed concrete, initial workability is just the beginning. These studies indicate that there is some slump loss due to agitation, ranging from a full loss without retempering [9] to no meaningful loss in three mixtures maintained for 150 minutes [29]. These results are not conflicting. They demonstrate that the answer must be determined through testing and not based on one time limit. Retempering restores slump, but restored slump does not mean that the other fresh properties are restored: Bayer [9] found that air content fell considerably even when slump was recovered. Thus, it is advisable to measure yield stress, plastic viscosity, setting behaviour and the air content as well as slump during a prolonged agitation period.

There is limited evidence for the effects of RHA. Prasittisopin and Trejo [11] reported that history had an effect on RHA-blended cement systems but their research was not done on actual RMC which does

not reflect the behaviour in commercial trucks. A dosage schedule set for the initial slump could secure the required slump at the batching plant yet give different retention over a long haul. This is an inference based on evidence reviewed and has not been tested for RHA; the same applies for the setting and early age properties effect of the dosage. Predicting the combined response of RHA and of extended agitation is not just a matter of summing up the effects of both.

4.2 Mechanical and durability performance

The pozzolanic reaction of RHA generates extra C-S-H and alters the pore structure, resulting in enhanced strength development at later ages when RHA is used at an appropriate replacement ratio [36], [13], [5]. It is the quality of the ash that makes the difference. The activity index of Wang et al. [16] was found to increase from 92%, to 114% with finer grinding and the ash burnt at 700 °C gave the best performance in Shawsh and David [18]. However, increased replacement percentages can be disadvantageous; Adina et al. [20] found that strength stopped increasing above 10% while Habeeb and Mahmud [17] found that using 20% of the cement replacement resulted in strength levels equivalent to the control sample.

There is an extra factor when extended agitation is used. Strength increased marginally following superplasticiser retempering [9]; transit time had no significant effect on 28-day strength [10]; and compressive strength was not significantly affected up to 150 minutes [29]. All three studies were on concrete without RHA, but their results suggest that loss of workability does not necessarily mean loss of strength in transit. Mixing history has an impact on RHA blended systems [11] and the optimum mixing history and optimum percentage of replacement cannot be established from the data presented here.

RHA can also enhance concrete durability through pore refinement as the extra C-S-H reduces pore connectivity and hence restricts the aggressive agents' penetration [5], [37], [38], [22]. Zareei et al. [13] found that moderate replacement of cement with RHA in concrete containing micro silica improved strength and durability, while Al-Alwan et al. [22] reported that fine RHA reduced chloride penetration, with a higher W/C ratio being detrimental. The macroscopic effects are usually explained by microstructural changes [5], [6] and calorimetry shows that ash treatment is significant [7]. The effects of prolonged agitation on this development have not been reported in the studies reviewed for RHA concrete. Similarly, no work was found that studied RHA with PLC under extended stirring, even though PLC is the most used type of cement in Nigeria [24]; the combination of clinker, limestone and RHA under these conditions remains unexplored.

4.3 Research gaps and practical implications

The evidence reviewed suggests that the behaviour of RHA-modified concrete during ready-mix transportation is likely to depend on the replacement level, among other factors. The following three items are important: the nature of the ash, the effect of extended agitation over time and compatibility and amount of chemical admixtures. Each one of these has been supported in the literature, but not enough to establish a relationship between the qualities of RHA, agitation in the truck and the performance of the concrete. Hence, it would be more defensible to state that RHA has been shown to have possible qualities for use as SCM and that prolonged agitation has been shown to have an effect on concrete, but not yet whether the effect is acceptable under realistic ready-mixed concrete conditions.

The following research gaps were identified. First, direct testing of RHA modified concrete under realistic transport is limited, and only one study reviewed by the authors (Prasittisopin and Trejo [11]) includes mixing history with RHA. Second, RHA studies rarely report mixing history and it has been demonstrated that it is important [11] and should be reported as an experimental variable. Third, the interaction between the superplasticiser chemistry, retempering and properties of the RHA should be evaluated under controlled agitation with yield stress, plastic viscosity, setting time, and air content. Fourth, properties should be followed in the same batches and should include fresh and hardened properties of the concrete such as compressive strength, tensile strength, permeability, chloride transport and microstructure. Fifth, the differences in ash production [16], [7], [8] make comparison between studies difficult, and thus burning regime and grinding, XRF, XRD, LOI, particle size, surface area and SEM should be reported consistently. Last, the trials on the field with truck mixers to test the laboratory results would be required.

The evidence suggests that the replacement percentage cannot be the sole criterion of replacement, as water demand and admixture requirement depends on the burning regime, fineness of the ash and processing history [17], [7], [6]. When proportioning the mixture, the planned transport time should be taken into account because a mix that has the right slump at the time of batching can lose a significant amount of slump before it is discharged [9], [10]. Retempering can restore workability [9], but it should be performed only to reach the desired slump and should not be assumed to restore other fresh properties of the concrete. There is no evidence from the studies reviewed to support a universal maximum RHA replacement level, agitation time or dosage of superplasticiser, and a performance-based approach would therefore be more suitable than prescribing a fixed combination.

5 Conclusion

Based on the evidence reviewed, it is concluded that:

1. When its characteristics and replacement ratio are controlled, RHA has potential as an SCM to enhance performance of concrete (strength and durability). The ash should be well burnt, and it is suggested that the temperature of the burning process is controlled at about 500 to 700 °C as reported by the studies reviewed, and be ground to an appropriate level; the quality of the ash should be checked using XRF, XRD and LOI etc.
2. The optimum replacement rate in the studies investigated falls generally between 7 and 15% of cement content with the characteristics of RHA influencing the initial water requirement and the mix rheology.
3. Independent investigations of extended mixing and ready-mix transit demonstrate that the amount of property change in fresh concrete is a function of the mix [10], [29] and that the slump can be re-established by superplasticiser retempering [30], [9] whereas mixing time and revolution count can affect RHA-based cementitious systems [11].
4. The study of the combination of RHA and extended ready-mix agitation is still limited. The primary demand is to understand the influence of these parameters – the properties of RHA, replacement rate, agitation time, drum rotation and superplasticiser control – have on fresh, mechanical, durability and microstructural properties, based on typical truck mixer conditions and PLC as the base binder.
5. Based on the available information, RHA is not considered to be unsuitable for ready mix applications. It should rather be designed and implemented using mixture designs and quality-control elements taking into consideration the time-dependent effects of transport, and general

limits on RHA content, transit duration and admixture management should be deferred until additional laboratory and field-scale tests are conducted.

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