# Mechanical effects of rice husk ash in ultra-high performance concretes: a matrix study

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ABSTRACT: Rice husk ash (RHA) has been observed to greatly improve both the mechanical and durability performance of conventional concrete mixtures, including increases in compressive strength while improving resistance to chloride ion transport and decreased permeability. This study explores the effects of using RHA as a mineral admixture in an ultra-high-performance concrete (UHPC) matrix, for which very high compressive strengths have already been achieved through dense particle packing and selection of materials. RHA is a promising material because of its widespread availability, its effectiveness as a pozzolanic material, and its potential for creating more environmentally sustainable building materials. Results of this study indicate that through the inclusion of RHA, the compressive strength of various mixtures at various water-binder ratios was improved and that RHA should be considered further for its use as a pozzolan in UHPC.

## 1 INTRODUCTION

Over the past several years there have been two threads of research within concrete material development, all providing beneficial information in their own right. The first of these developments has been that of ultra-high-performance concretes (UHPC). Designed with the intent of providing an alternative to steel construction and to concrete intensive applications, these UHPCs have been able to attain very high compressive and flexural strengths. These mixtures are typically characterized by very small, densely packed particles, intense cement requirements, and special curing regimes. Through creating a higher performing concrete, less concrete can be used overall, and by creating elements in a precast facility, on-site construction times can be reduced.

The second trend in research has been the inclusion of supplementary cementitious materials (SCM) into blended cements and general mixtures. SCMs provide a way to reduce the cement demand while maintaining a specified performance. Many of the materials considered for SCMs are industrial waste-stream products. While these materials have very appealing benefits, they are often expensive, especially outside of industrialized nations. Additionally, many of these products require further processing before they can be used in cementing applications, which may reduce their effectiveness as a non energy-intensive alternative to cement. In addition to reducing the cement demand of a particular mixture, these SCMs are able to give the same durability benefits of using densified (DSP) mixtures, namely reduced porosity and the associated effects.

## 2 RESEARCH SIGNIFICANCE

The research undertaken by this study seeks to create a bridge between the two areas of research discussed above, integrating an agricultural waste stream product into an already high-performing concrete. In doing so, it is expected that more research will be undertaken to expand the current knowledge of the use of such agricultural SCMs in creating UHPCs. This paper seeks to pose the question as well as provide some initial findings.

## 3 EXPERIMENTAL PROCEDURES

### 3.1 *Specimen Preparation*

For this study a mixture proposed by Neeley & Walley (1995) and modified by O’Neil (2008) was further adjusted; this mixture can be found in Table 1. It should be noted that this study focuses only on the composite matrix, thus fibers were omitted from the mixture design. Each matrix prepared for this study was mixed in a 10 liter capacity Hobart mixer. The dry constituents were added in order of increasing density, to avoid loss of fines upon mixer start up, as suggested by O'Neil (2008). The dry materials were mixed for 3 minutes to ensure uniform distribution prior to the addition of water. After 3 minutes, half of the water was added to the mixture, then all of the HRWRA, then the remainder of the water was used to rinse out the HRWRA container, to ensure that all of the measured material was added to the mixture. Depending upon the amount of water and RHA, each mixture had a different time-to-paste time, but most mixtures required 5-10 minutes of continuous mixing before a plastic paste was achieved. The amount of HRWRA added varied from mixture to mixture, as each mixture exhibited different levels of demand, but the water contributed to mixture with an increased amount of HRWRA is considered negligible, and is therefore not included in the mix water.

It should be noted, however, that some of the mixtures with 20% RHA did not achieve a plastic state prior to the completion of mixing. With the addition of more HRWRA this would have been possible, but it was observed that above a certain limit of HRWRA addition, the setting of the resulting mixture was significantly retarded, to the extent that the use of such a mixture simply would not be practical.

### 3.2 *Evaluation of Compressive Strength*

Within this study, the two primary tests that were completed were those for compressive strength and fracture toughness. Compression testing was carried out on a Forney F-50F-F96 force control machine. These tests were conducted on no less than three 2-inch cubes in accordance with ASTM C 109, with the exception that the loading rate of 35±7 psi per second was used. Due to rate effects, the compressive strengths reported herein can be taken as conservative.

### 3.3 *Evaluation of Fracture Toughness*

Currently, there are no existing standard methods for measuring the stress intensity factor for concrete, so ASTM E 399, *Linear-Elastic Plane-strain Fracture Toughness $K_{IC}$ of Metallic Materials*, is adopted for this purpose. The use of the method has been previously explored and confirmed for use with cementitious matrices by Li et al. (1995). Figure 1 illustrates the testing arrangement used in this study. For each matrix evaluated in this way, at least four 3-inch by 1.5-inch by 12-inch specimens were prepared with a midspan notch cut to approximately 30mm and loaded at a rate corresponding to 0.002mm/s on an MTS 810 using load transducer in a closed loop cycle. The actual notch length was measured and used for calculating the fracture toughness.

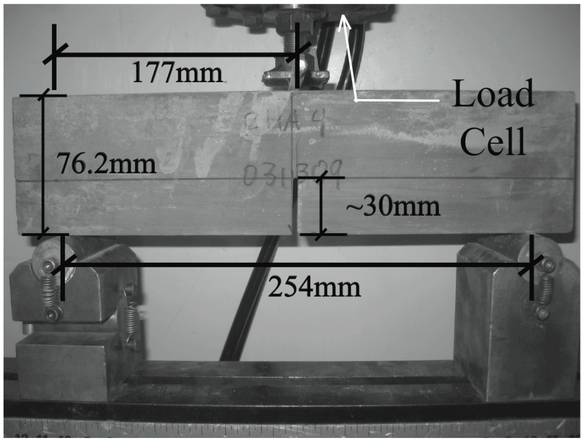

Figure 1. Experimental test set-up for measuring matrix fracture toughness.

The fracture toughness is calibrated for use with the geometry employed and calculated using the following equation:

$$K_Q = \frac{P_Q S}{BW^{3/2}} \cdot f\left(\frac{a}{W}\right) \tag{1}$$

where $P_Q$ = peak load, S = span, B = specimen thickness, W = specimen depth, and *f*(a/W) is the geometric calibration factor, which ranged between 1.91 and 2.18 depending upon the actual crack length of each specimen.

## 4 EFFECTS OF RHA IN UHPC MATRIX

The study contained herein was primarily focused on the basic mechanical effects of including rice husk ash into a modified UHPC mixture design. The first part of the study sought to find an optimized value of rice husk ash addition, i.e., the mixture giving the highest compressive strength, keeping in mind workability concerns. The effect on fracture toughness was also considered, as it is an influential behavior in the tensile performance of fiber reinforced cement-based composites. The main part of this study will examine various levels of RHA addition at different water/binder (w/b) ratios. Once the critical w/b ratio and addition levels were established, mixtures considering the replacement of cement with RHA were also made and tested. After an optimized value of RHA was determined, the effects of various curing conditions were examined to see what effects, if any, the inclusion of RHA had in these curing conditions.

### 4.1 *Optimization of RHA content and w/b ratio*

The mixture proportions (Table1) from O'Neil (2008) were adopted as the reference mixture (with w/b =0.20, rather than 0.16 as given), with adjustments using RHA as described below. The physical and chemical properties of cementitious materials used in this study are given in Table 2.

The mixtures were cured in the "7-4-2" scheme, as established by O'Neil, i.e., the specimens were cured after set in room temperature water until seven days age, then in 90°C water for four days, followed by 90°C air for two days. The specimens were then tested at 14 days age, assuming that the elevated temperatures had allowed them to reach sufficient maturity.

Table 1. Mixture proportions (ratio by mass) from O'Neil (2008).

| Cement | Silica Fume | Silica Sand | Silica Flour | Water | HRWRA |
|---|---|---|---|---|---|
| 1 | 0.389 | 0.967 | 0.277 | 0.22 | 0.016 |

Table 2. Typical physical and chemical properties of cementitious (binder) materials used.

| | Type H Cement (C) | Silica Fume (SF) | Rice Husk Ash (RHA) |
|---|---|---|---|
| Specific Gravity | 3.15 | 2.2 | 2.15 |
| Specific Surface Area ($m^2/kg$) | - | 15,000-30,000 | 43,000 |
| Mean Particle Size (µm) | 30 | 0.4 | 120 |
| Chemistry (% of mass) | | | |
| $SiO_2$ | 20.83 | >85 | 92 |
| CaO | 62.91 | 0.426 | 2.1 |
| $Al_2O_3$ | 2.8 | 0.208 | 1.1 |
| $Fe_2O_3$ | 4.4 | 0.055 | 0.4 |
| MgO | 4.5 | 0.235 | 0.2 |
| $Na_2O$ | - | 0.129 | 0.14 |
| $SO_3$ | 2.9 | - | - |
| $TiO_2$ | - | - | - |
| $K_2O$ | - | 0.652 | - |
| LOI | 1.15 | <0.7 | 4 |
| Phases based on Bogue Calculations | | | |
| $C_2S$ | 11.18 | | |
| $C_3S$ | 64.34 | | |
| $C_3A$ | <0.01 | | |
| $C_4AF$ | 13.5 | | |
| $CaSO_4$ | 4.95 | | |

Several researchers have reported that there is a significant increase in the water demand of a mixture for a given workability when RHA is used. In consideration of the increased water demand, w/b ratios of 0.20, 0.25, and 0.30 were used, although these are typically considered much too high for typical UHPC mixtures. This increase in water demand was attributed to RHA's very high specific surface area and carbon content (Zhang & Malhotra, 1996). The typical chemistry of RHA produced by the power plant used for this study can be found among the physical and chemical properties of the other cementitious materials used in this study in Table 2. The aggregates used in this investigation were silica flour (40 µm average size) and silica sand (269 µm average size). The superplasticizer used was a low-viscosity, polycarboxylate-based liquid high range water reducing admixture.

In his seminal work, P.K. Mehta (1978) suggested that rice husk ash does not need to be ground prior to its incorporation into cementing, though it was recommended to avoid its aggressive water absorption, such as was found by the authors in the present work. The majority of researchers to date have employed various methods of grinding RHA prior to using it, but this is typically done with the motivation that smaller particles are better for packing, in keeping with the densified small particle (DSP) philosophy.

There has been no clear consensus on an optimal level of grinding, but it has been observed that even with a significant amount of grinding, the unground specific surface area of a fluidized bed burned rice husk ash is higher than that which has been finely ground (Meryman, 2007). As can be see in the SEM micrograph in Figure 2, unground RHA has what can be considered a naturally optimized surface area resulting from the honeycomb-like internal structure (right side of micrograph) and nodule external structure (lower left side of micrograph). This microstructure enables the RHA to play an important role in the hydration reaction both by increasing its chemical reactivity and by providing host sites for the nucleation of hydration products. For this study, then, it was decided that, despite the traditional DSP theory that typically governs UHPC mixture design, a larger, unground RHA particle would be used.

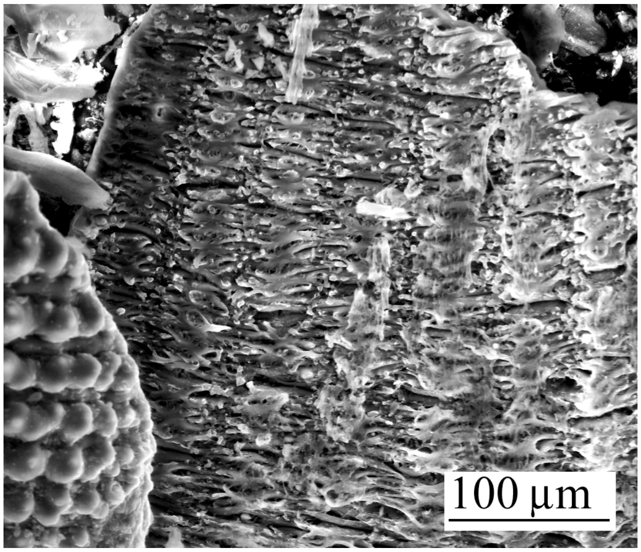

Figure 2. Micrograph of rice husk ash particles.

The mixture proportions used for the first part of this study are similar to that given in Table 1 and are presented in Table 3. The exceptions are additions of

RHA in percentages of the original binder materials (cement + silica fume), the water varied as the amount of new binder materials (cement + silica fume + RHA) changes to maintain the desired water-binder ratio, and the amount of superplasticizer used is adjusted as needed to attain a semi-flowable paste consistency.

Table 3. Proportions and results of mixtures used in study.

| Mixture Name | Water-Binder Ratio | RHA | f'c | $K_{IC}$ | Dynamic Young's Modulus |
|---|---|---|---|---|---|
| | kg/kg | % (C+SF) | MPa | MPa√m | GPa |
| *Optimization Study* | | | | | |
| RHA0-20 | 0.20 | 0 | 129* | 1.1 | 49 |
| RHA5-20 | 0.20 | 5 | 114 | 1.02 | 46 |
| RHA10-20 | 0.20 | 10 | 137* | 1.01 | 46 |
| RHA20-20 | 0.20 | 20 | 155 | 0.88 | 43 |
| RHA0-25 | 0.25 | 0 | 101 | 0.88 | 41 |
| RHA5-25 | 0.25 | 5 | 83 | 1.01 | 39 |
| RHA10-25 | 0.25 | 10 | 145 | 0.88 | 38 |
| RHA20-25 | 0.25 | 20 | 112 | 0.75 | 40 |
| RHA0-30 | 0.30 | 0 | 86 | 0.85 | 37 |
| RHA5-30 | 0.30 | 5 | 109 | 0.70 | 34 |
| RHA10-30 | 0.30 | 10 | 94 | 0.82 | 35 |
| RHA20-30 | 0.30 | 20 | 87 | 0.60 | 26 |
| *Cement Replacement Study* | | | | | |
| RHA-C10-20 | 0.20 | 10 | 116 | 1.08 | 46 |
| RHA-C20-20 | 0.20 | 20 | 112 | 1.07 | 38 |
| RHA-C30-20 | 0.20 | 30 | - | - | - |
| *Curing Study* | | | | | |
| RHA0-20 14H2O | 0.20 | 0 | 90 | 1.06 | 53 |
| RHA0-20 742 | 0.20 | 0 | 129* | 1.11 | 49 |
| RHA0-20 742$^{+}$ | 0.20 | 0 | 137 | 1.28 | 45 |
| RHA10-20 14H2O | 0.20 | 10 | 109 | 1.05 | 47 |
| RHA10-20 742 | 0.20 | 10 | 137* | 1.01 | 46 |
| RHA10-20 742$^{+}$ | 0.20 | 10 | 168 | 1.32 | 39 |
| Unmodified Averages | | | | | |
| RHA0-20 | | | 116 | 1.16 | |
| RHA0-20 742 | | | 141 | 1.04 | |
| RHA10-20 | | | 140 | 0.87 | |
| RHA10-20 742 | | | 133 | 1.15 | |

* These values represent the average of the tests conducted in both the optimization study as well as the curing study. This was done to improve the statistical strength of the results by expanding the number of samples.

### 4.2 *Results of optimization of RHA and w/b ratio*

As can be expected within any cementitious composite, an increase in the relative water content of a particular mixture will decrease its compressive strength; this study shows no exception. For a given w/b ratio, however, it was observed that the compressive strength of each mixture tested was generally improved by the addition of RHA (Table 3 and Figure 3), with an optimal amount dependent on the w/b ratio. From these data, it is clear that the inclusion of RHA is beneficial to these mixtures, providing a basis for its merits as a pozzolan.

As can be seen in Figure 3, there is a trend among the various mixtures indicating that as the relative amount of water in the mixture increases, the optimal (giving the highest compressive strength) level of RHA addition decreases. This is shown that while at the w/b ratio of 0.20, the compressive strength of the mixtures increased in proportion to the amount of RHA added. Conversely, at the w/b ratio of 0.30 the compressive strength of the mixtures decreased in proportion to the amount of RHA added. The behavior seen of the mixtures at the w/b ratio of 0.25 can then be thought of as a transitional region, where neither the high nor low amount of RHA addition gives as much benefit to compressive strength as does the median level of addition.

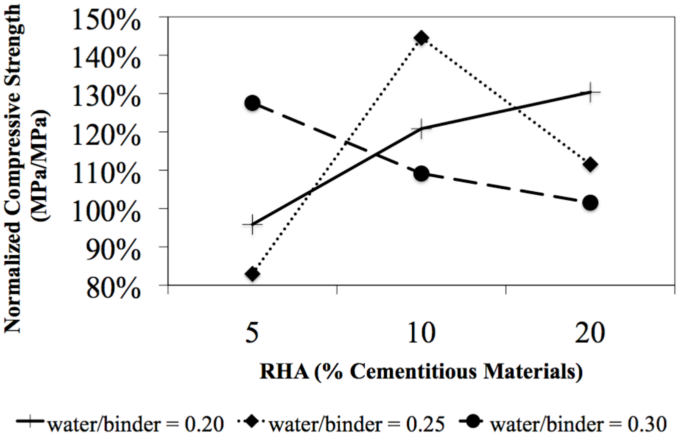

Figure 3. Performance of RHA mixtures in various levels of addition and at various water-binder ratios (normalized to relative control mixture).

This behavior could be due to absorbent nature of the ash. Having a high amount of semi-internal surface area, RHA has been observed to be a particularly effective absorbent, and it is even marketed as such by Agrilectric Inc., the supplier of the material used in this study. The significance of this behavior is that when the water is initially added to the dry mixture, there is opportunity for the RHA to absorb an amount of water out of the mixture, preventing it from immediately participating in the hydration of the cement particles.

Once hydration begins to start in earnest, however, the hydroxide ions released into the hydration solution begin to attach to the silicate ions on the surface of the pozzolans (Taylor, 1997). For silica fume, this results in nothing more than decomposition. However, in RHA, due to that water that was initially absorbed into the semi-internal honeycomb, the decomposition of the silicate structure of the particle may lead to the release of additional water into the matrix.

The benefit of this delayed hydration is that by this time in the hydration process, C-S-H is likely to have already formed on the surface of the cement particles, inhibiting the diffusion of this water that would allow further hydration of the cement. This water, instead may allow increased transport of the dissolved portlandite to the pozzolans where further conversion to C-S-H can occur.

This effect, however, becomes less potent as the relative amount of water provided in the mixture increases. As the mix water increases, there is an increase in abundance of "free" water available for cement hydration, and results in the formation of capillary pores. The result of which may be that the extra water may now enable the initial consumption of more silica fume, which could have otherwise been relegated to a more physical rather than pozzolanic task.

So the RHA may now act more like a weak site within the matrix, being large and relatively weak in structure, potentially having fewer products formed within it to reinforce it, and less silica fume to pack around it. In this situation, the strength gained from the additional pozzolan could be offset by the weakness of this large particle.

The above discussion may explain why as the water-binder ratio increases it is seen that the optimum level of RHA addition decreases in kind. Initially, when there is less abundance of water in the matrix (at a w/b ratio of 0.20), high amounts of RHA are more effective. But at a relatively higher amount of water within the matrix relatively lower amounts of RHA are beneficial.

A possible explanation for why the RHA5- series mixtures do not show any improvement in strength until the highest water-binder ratio level test, could be that in such a small quantity relative to the rest of the mixture, the absorption effect is not so significant as it is with greater amounts of RHA. This would result in the matrix strength being dominated by the effects of small particle packing, leaving the RHA, though strong, as flaw-like sites being such a large and weak material.

In the above reasoning, there is the implication that there is an optimal balance for each water-binder ratio, occurring at each one for various reasons. This study, then, proposes that further research ought to be conducted to understand what the strengthening mechanisms behind the inclusion of RHA are, and how to best utilize those mechanisms for the specific aim of each application in which it is applied.

While the above discussion is highly speculative, as is any discussion on the subject of cementitious hydration kinetics, there are some observations made while using an SEM that may suggest the occurrence of such a process. Small specimens of size 0.5cm × 0.5cm × 0.5cm were prepared using a water-cooled precision diamond saw and studied under an SEM in low vacuum mode. The observation is that in a mixture containing no RHA, there was a prevalence of small, well-defined crystals throughout the surface of the sample. Using the energy-dispersive x-ray spectroscopy (EDAX EDS) feature of the SEM to determine the approximate atomicity of these crystals, it was found that the ratio of atoms seems to suggest that these crystals are calcite; the micrograph and accompanying spectrum can be seen in figures 4 & 5.

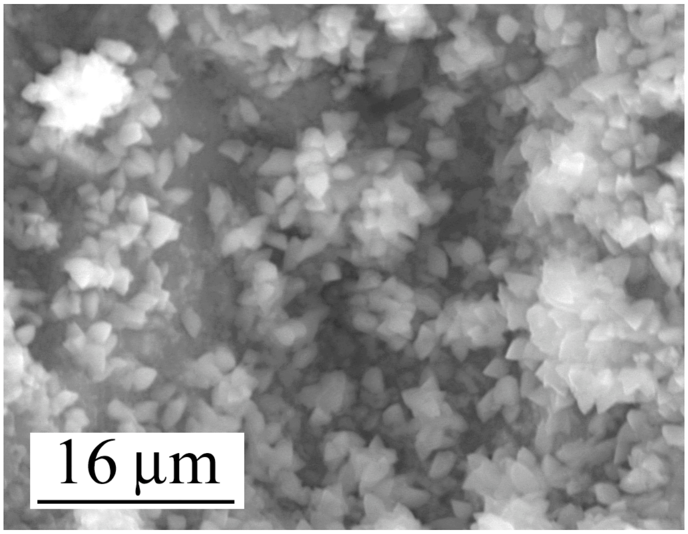

Figure 4. Micrograph of potential calcite growth.

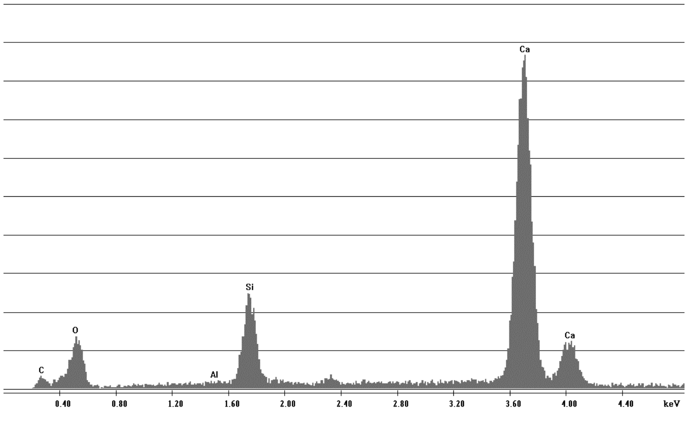

Figure 5. EDS spectrum of potential calcite growth on specimen surface.

It is quite unlikely that these crystals were formed during the initial hydration, but in the process of cutting and air-drying the samples in preparation for use in the SEM, it is possible that reaction of carbonic acid (from atmospheric $CO_2$ dissolved in the cutting water) with CH could have enabled this. In samples containing RHA, there were very little, if any, of these crystals observed (Figure 6). This may indicate the efficacy of including RHA for consuming CH, and supports the theory presented above in explanation of this improved performance.

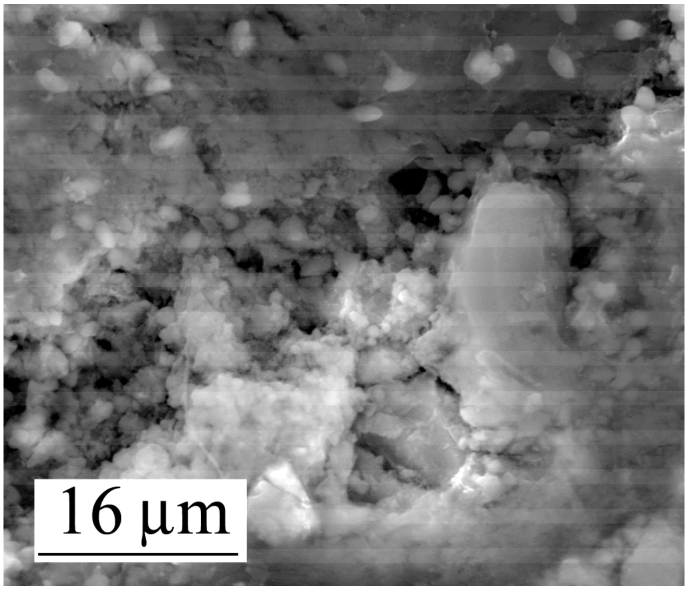

Figure 6. Micrograph of RHA20-20 showing little potential calcite growth.

### 4.3 *Replacing Cement with Rice Husk Ash*

This study also sought to consider the potentials of not only using RHA to add to the matrix as a pozzolan, but also to examine the possibility of using it instead of cement, thereby reducing the overall demand. As was confirmed by the optimization results, the most prominent results of the RHA inclusion were at the lowest water-binder ratio tested, 0.20. Consequentially, this ratio will be used to evaluate the use of replacing cement with RHA. Within this part of the study, three potential mixtures were evaluated, replacing cement at 10%, 20%, and 30%, their specific mixture proportions can be found in Table 4 below.

Table 4. Cement replacement mixture proportions.

| Constituent | Mass ratio by mixture | | |
|---|---|---|---|
| | RHA-C10-20 | RHA-C20-20 | RHA-C30-20 |
| Cement | 0.9 | 0.8 | 0.7 |
| Silica Fume | 0.389 | 0.389 | 0.389 |
| Rice Husk Ash | 0.1 | 0.2 | 0.3 |
| Silica Flour | 0.277 | 0.277 | 0.277 |
| Silica Sand | 0.967 | 0.967 | 0.967 |
| Water | 0.2778 | 0.2778 | 0.2778 |
| HRWRA | 0.055 | 0.084 | >0.1 |

In the process of mixing it was found that the mixture containing 30% RHA replacing cement could not reach a castable state without incurring a massive amount of superplasticizer, which would have delayed the setting time enough to preclude it from the curing scheme used in this study, and probably most other applications. As a result, this mixture was abandoned for the present study. Each of the other mixtures was cured in the 7-4-2 manner described above, and compression and fracture toughness tests were carried out as previously described.

### 4.4 *Effects of Replacing Cement with Rice Husk Ash*

The results of our study indicate that cement can be successfully replaced by both 10% and 20% RHA (Table 3). Furthermore, it is interesting to note that despite the loss of cement, and the decrease in fracture toughness, the compressive strength of the resulting matrix was maintained. The maintenance of compressive strength is in keeping with the results above, where at a water-binder ratio of 0.20 significant increases in compressive strength were seen at both 10% and 20% addition of RHA. With the decrease in strength that comes with the removal of cement, it is seen that this is adequately compensated by the addition of RHA.

Previous researchers have found similar results for mixtures of higher water-binder ratios. Two separate studies have both found that while using ground RHA, increases in compressive were found when any cement was replaced by RHA, but both agree that the best performance was gained when the replacement level was 20% (Bui, et. al. 2005, Ganesan, et. al 2008). Though the mechanisms of strengthening are assumed to be different in nature, it is interesting to see that at lower water-binder ratios the 20% level of replacement still gives good performance. The implications of this observation are that there may yet be the possibility of reducing the cement demand in UHPC design that normally requires extensive amounts of the same due to the absence of coarse aggregates and to ensure high strength.

### 4.5 *The Effect of Various Curing Regimes on a selected RHA mixture*

Building upon the results of the optimization study, it was decided that the mixture containing 10% RHA by addition at a water-binder ratio of 0.20 had the most promise for use, and therefore it was selected for this portion of the study. Although the mixture at the same relative water level containing 20% RHA performed better, the mixture with 10% was much easier to work with and cast, and it was estimated that that difference would become increasingly important when a mixture containing fibers is considered.

This portion of the study included the RHA10-20 mixture as well as its relative control, RHA0-20, to examine the effects of three different curing conditions. In addition to the 7-4-2 scheme described above, the specimens were cured for 14 days submerged in water; a 7-4-$2^+$ scheme was also adopted. The latter consists of the same seven days in water and four days in 90 °C water, but the final two days were adjusted to include two days in 200 °C air. The increase in temperature was performed to increase the possibility of the formation of the higher ordered C-S-H phases. These mixtures were prepared with the same proportions given above, scaled for the larger mixed used; the matrices were mixed in a 2 cu. ft capacity pan mixer, with 3 cubes and 4 beams cast for each curing scheme.

## 4.6 *Results of Curing Study*

In completing the aforementioned curing schemes, it was observed that RHA10-20 outperformed the control for both strict water curing and the 7-4-$2^+$ curing schemes, but exhibited a lower strength after the 7-4-2 regime. This can be accounted for in part by the fact that some of the RHA10-20 cubes adhered together during curing and when separated some minor damage was incurred. As a result, the averages of both mixtures' compressive strength from this portion of the study and the optimization study will be used; the initial values are reported as well, the data are presented in Table 3 above.

It is no surprise that RHA10-20 outperformed the control mixture in a water curing scheme, given the highly reactive nature of RHA resulting from its high surface area and high content of amorphous silica (Mehta & Pitt, 1976). In this, then, there is the possibility of using RHA for mixtures that must be cast-in-place where specialized curing regimes are not possible, but high strengths are still required.

Again, it is interesting to note that the mixture with RHA seems to be more receptive of the higher temperature curing conditions found in the 7-4-$2^+$ curing scheme. One possible explanation for this is the increased amount of silica within in the mixture for the possible formation of higher ordered C-S-H phases.

## 4.7 *Effects of RHA on Fracture Toughness*

When designing materials for specific uses, it is not always enough to improve the compressive strength of the bulk material, but there are occasions on which it is important to adjust the compressive and tensile performances independent of each other. General material design theory has accepted the conclusion that an increase in compressive strength leads to an increase in fracture toughness. However, the effect of RHA on the matrices in which it has been included proves itself to be a unique material in that the fracture toughness of the matrix, generally speaking, decreases in proportion to the amount of RHA used while the compressive strength increases; these results can be found in Table 3. Another researcher (Giaccio, 2007) found similar behavior in conventional high-strength concretes incorporating RHA, ranging in water-binder ratios from 0.28 to 0.56, though the reductions in fracture energy reported therein were not as significant as those found in this study.

The decreases in fracture toughness are most consistent at the lowest water-binder ratio, 0.20, which can be attributed to this base matrix being the most densely packed. With the inclusion of these larger and weaker structured particles, though the compressive strength may increase because of hydration products forming in and around this weak carbon structure, when put under tension this "composite" is easily pulled apart. Due to the densification of the matrix around it, the bulk material fracture toughness is quite high, as indicated by the control, yet the toughness of the individual RHA could be relatively smaller. This contrast between the toughness of each material could lead to stress concentration at these weaker sites, leading to the significant reductions in the overall matrix fracture toughness observed here. It is also possible that the shape of the RHA may have a tendency to induce flaw-like defects more sensitive to tension than compression, giving similar behavior.

## 4.8 *Effects of RHA on Dynamic Young's Modulus*

From the notched beams broken for finding the fracture toughness, 38mm × 38mm × 127mm prisms were cut and the dynamic Young's Modulus was calculated using the longitudinal resonance frequency, in accordance with ASTM C 215, the results of which are given in table 3. It will be seen that there are no appreciable drops in the stiffness of the material with the addition of RHA, the greatest being a 20% reduction for RHA20-30. This shows, then, that though the density of the matrix is decreased by the inclusion of RHA, the stiffness of the material is maintained.

When considering the stiffness of the matrices in which cement is replaced by RHA, it will be noticed that there are some significant decreases. This can be expected since there is less cement and therefore less unhydrated cement in the matrix, which can result in lower modulus, as unhydrated cement has been attributed as a stiffening factor in low water-binder ratio mixtures (O'Neil, 2008). If RHA is to be used as a cement replacement, we recommended that no more than 10% be replaced for high performance mixtures, as the Young's modulus is an important factor for structural design.

## 5 SUMMARY AND CONCLUSIONS

In the this study of the inclusion of RHA into potential UHPC matrices, we observed the following:

1. RHA can be used in an unground form with beneficial results.
2. RHA is an effective pozzolan, even at lower water-binder ratios as the addition of RHA into matrices maintained or increased compressive strength.
3. The addition of RHA did not lead to significant reductions in matrix stiffness, but did lead to reductions in the material's fracture toughness.
4. RHA can be used as a replacement for cement even at low water-binder ratios.
5. RHA may allow the independent tailoring of matrix compressive and tensile performances.
6. The increased water demand of RHA may be limited by the amount added as well as the desired water-binder ratio of the matrix.

From the above results it can be seen that though unsupported by the prevailing theories in ultra high performance material design, rice husk ash can play an important role in designing more sustainable materials for the future. Even if functioning simply as a material included to increase the yield of a mixture, RHA is effective at maintaining, if not increasing compressive strength. Additionally, by decreasing the density of the matrix while maintaining both stiffness and compressive strength at lower water-binder ratios, the inclusion of RHA could mean reduced dead-weight in elements made therefrom, potentially reducing transport weight in precast elements while maintaining the desired performance. That rice husk ash mixtures are also more responsive to higher heat treatment could also be of benefit to precast applications.

Aside from mechanical performance benefits, it should be noted that, at the present time, RHA is an agricultural waste-stream product that is available in many countries where other pozzolans may not be as common or inexpensive. In instances such as Agrilectric Power Partners, the provider of the RHA used in this study, the hulls from the milled rice have already been used to generate power and the resulting ash that can be used in concreting applications is then a tertiary use, maximizing the benefit of what would otherwise be waste.

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