The effectiveness of using Raw Sewage Sludge (RSS) as a water replacement in cement mortar mixes containing Unprocessed Fly Ash (u-FA).

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Abstract

The performance of two groups of mortar mixes containing Unprocessed Fly Ash (u-FA) with either Raw Sewage Sludge (RSS) or water was examined. Both groups included four mortar mixes containing Portland cement, sand, u-FA. Group 1 used RSS as a water replacement and Group 2 used water. Cement was replaced with 0, 10, 20 and 30% u-FA of total binder weight and one Liquid/Binder ratio of 0.8 was used. Mortar mixes were tested for their flowability, Total Water Absorption (TWA), Ultrasonic Pulse Velocity (UPV), compressive strength and drying shrinkage. The outcomes of the investigation were encouraging in that cement-based materials containing RSS demonstrated good engineering properties in comparison to the control mixes. The inclusion of u-FA significantly reduced flowability; however improved long-term compressive strength for both groups. The greatest compressive strength was recorded for the mixes with 10-20% u-FA replacement.

Keywords

Raw Sewage Sludge (RSS), Unprocessed Fly Ash (u-FA), Sustainable Construction Materials.

1 Introduction

1.1 Sewage sludge

Raw Sewage Sludge (RSS[*]) is a residual stream of suspended or dissolved organic and inorganic materials that result from the treatment processes of municipal wastewaters. RSS is usually in the form of liquid or semisolid liquid that typically contains from 2 to 8 percent solids by weight, depending on the operation and processes applied. In wastewater treatment plants, RSS is mainly collected from primary settlement tanks, which are large round or rectangular in shape and allow heavier particles to settle to the bottom and later swept by scrapers to a submerged outlet. The settled stream is pumped, in the form of thick slurry, to the sludge storage and treatment unit for further processing. RSS may also be collected from secondary and tertiary settlement tanks [1].

At sewage sludge storage and treatment units, further biological, chemical and physical processes are applied to reduce the water content and eliminate potential associated hazards of RSS. Hazards include high heavy metal contents, presence of dangerous pathogens and risks associated with the biodegradation of organic matters (production of flammable gases and unpleasant odours). Treatment processes include preliminary operations, thickening, stabilisation, conditioning, dewatering, heat drying and other processing and thermal reduction [1].

There are approximately 35 million tonnes of RSS produced in the UK each year. These quantities are reduced to 25 million tonnes per year by applying further on site physical and chemical processes [2]. In 2010, 1.41 million tons of dry solids were produced from sewage sludge in England and Wales [3].

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[*] Abbreviations: RSS is Raw Sewage Sludge, u-FA is Unprocessed Fly Ash, TWA is Total Water Absorption, and UPV is Ultrasonic Pulse Velocity.

Prior to the implementation of the European Union Urban Waste Water Treatment Directive (91/271/EEC) in 31 Dec 1998, around a quarter of the sewage sludge produced in the UK was either discharged to surface waters via pipes or disposed from ships at sea [3]. The discontinuation of this route, together with the stringent standards required by the European Waste Water Directive, generated excessive quantities of sewage sludge, adding greater challenges for environmental agencies and local authorities. Since then, the traditional re-use and disposal methods have had to be replaced by effective alternatives to improve waste management practices currently in place. Alternative methods include the utilisation of sewage sludge products in the construction industry for the production of sustainable construction materials [4].

Sewage sludge products have been recently introduced as sustainable alternatives to the traditional raw ingredients used in the construction industry. These include dewatered sewage sludge, dry sewage sludge and incinerated sewage sludge ash. These materials were used in different construction applications including the production of cement-based materials [5-10], ceramic products such as ceramics tile bodies [11-18], lightweight construction materials [19-23], soil stabilisation [24-26], and other civil engineering applications such as wastewater treatment [27] and landfill lining [28].

1.2 Unprocessed Fly Ash

In addition to the problems caused by excessive RSS production in the UK, the power generation industry also produces vast quantities of fly ash from burning coal. In the UK, there is approximately 5,300,000 tonnes of fly ash produced annually [29]. Unprocessed Fly Ash (u-FA) is not suitable for use in construction applications due to its high carbon content and large particle size [30-33]. Therefore there is a requirement for the u-FA to be treated and classified to meet the requirements of the European Standards, and this process often involves a series of costly and energy consuming mechanical and physical applications. Although there is very limited information about the utilisation of u-FA, the current literature suggests that incorporating this in cement-based materials would improve its mechanical and durability properties [34, 35].

2 Experimental

2.1 Materials and mixing proportion

In this experimental work, the performance of two groups of mortar mixes containing 0-30% u-FA of total binder weight with either RSS or water were examined. Group 1 and Group 2 used the same composition of Portland Cement, sand and u-FA. Group 1 used RSS as a water replacement whereas Group 2 used water and was considered as the control (Table 1). Mortar mixes were tested for their fresh and engineering properties including flowability, TWA, UPV, compressive strength and drying shrinkage.

Table 1: Mixing composition.

Group	Mix	Binder		Sand	Liquid/Binder	Liquid type
		Cement	u-FA			
1	MR1	1	0	4.5	0.8	RSS
	MR2	0.9	0.1			
	MR3	0.8	0.2			
	MR4	0.7	0.3			
2	M1	1	0	4.5	0.8	Water
	M2	0.9	0.1			
	M3	0.8	0.2			
	M4	0.7	0.3			

The cement used throughout the experimental programme was Portland Cement that complies with the requirements of BS EN 197-1:2000 type CEM I Portland cement strength class 42.5 [36]. The fly ash used in this experimental work was u-FA that was collected from a coal power station in the UK. The RSS sample was collected from a Sewage Treatment Works in the West Midlands, UK in the form of thick slurry containing 97.5% liquid of total weight (Figure 1).

Table 2 shows the physical and chemical properties of u-FA and RSS used, and Figure 2 shows the particle size distribution of u-FA. 0.5% Hydrated Lime of total RSS weight was added for partial treatment of RSS to eliminate pathogens by raising the pH level >12. The amount of the hydrated lime added was estimated based on recommendations made by the British Lime Association [37]. The sand used throughout this work was size 0/4 that complies with the requirements of BS EN 12620:2002+A1:2008 category G_F85 [38], and fineness content category 1 [39]. The mixing water used for the control was tap water that complies with the requirements of BS EN 1008:2002 [40] and BS EN 206-1:2000 [41].

Figure 1: Raw Sewage Sludge sample.

Table 2: Physical and chemical properties of u-FA and RSS.

Material	Property/element	Unit	Value	Techniques
u-FA	Moisture content	% weight	0.78	-
	Bulk density	Kg/m^3	442	BS EN 1097-3:1998 [42]
	Dry particle density	Kg/m^3	1824	100ml Pycnometer
	SiO_2	% total weight	45.06	X-Ray Fluorescence (XRF)
	Al_2O_3		16.94	
	Fe_2O_3		9.04	
	CaO		1.96	
	K2O		1.4	
	MgO		1.02	
	TiO_2		0.71	
	Na_2O		0.34	
	P_2O_5		0.19	
	BaO		0.08	
	ZrO_2		0.07	
	SrO		0.06	
	MnO		0.05	
	ZnO		0.04	

	Cr_2O_3		0.02	
	CuO		0.02	
	PbO		0.02	
	Loss on Ingestion (LOI)	% total weight	23	Thermogravimetry
RSS	Liquid content	%	97.5	Drying oven
	Density	Kg/m^3	1012	BS EN 1097-7:2008 [43]
	Chloride	ppm	32.19	Ion Chromatography System (ICS)
	Nitrate		2.94	
	Phosphate		1.38	
	Sulphate		23.93	
	Cr	ppm	1.19	Inductively Coupled Plasma (ICP)
	Cu		5.33	
	Ni		2.51	
	Sn		0.04	
	Zn		19.08	
	Mn		3.92	
	Fe		147.72	
	Al		77.83	
	As		0.27	
	Ba		7.55	
	S		65.22	
	P		200.83	
	Na		199.65	
	Mg		54.77	
	K		121.05	
	Ca		33793.35	
Dry solids of sewage sludge	Na_2O	% total weight	23.46	X-Ray Fluorescence (XRF)
	MgO		3.35	
	Al_2O_3		2.53	
	SiO_2		8.54	
	P_2O_5		8.04	
	SO_3		4.45	
	Cl		0.15	
	K_2O		0.58	
	CaO		33.78	
	TiO_2		0.4	
	Fe_2O_3		11.11	
	ZnO		0.26	

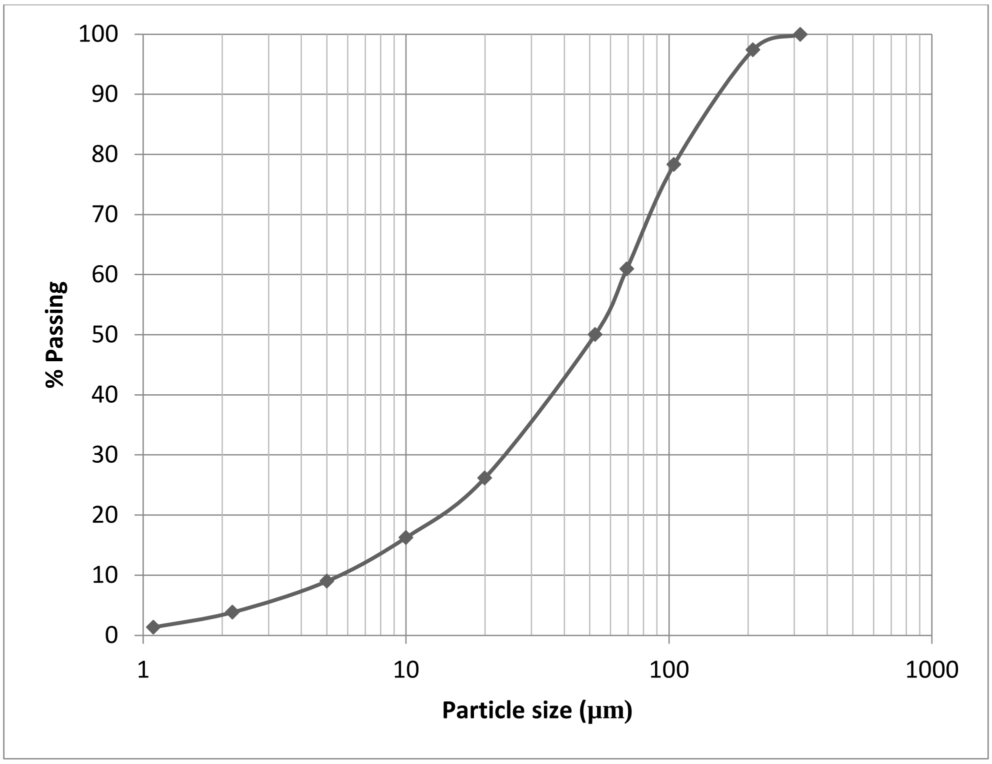

Figure 2: Particle size distribution of the u-FA sample.

2.2 Casting, curing and testing

Steel moulds of 50mm in size were used to prepare mortar specimens for the determination of Total Water Absorption (TWA), Ultrasonic Pulse Velocity (UPV) and compressive strength. For the determination of drying shrinkage, prisms of dimensions 40mm x 40mm x 160 mm in size were used. Cast specimens were covered with plastic sheets and placed in a room (temperature of 20°C ± 2°C) for 24 hours until demoulding. Thereafter, cubes were cured for 1, 7, 28, 90 and 365 days by wrapping them using cling film. The prisms were left exposed for 360 days during which regular shrinkage readings were taken using a dial gauge.

The flowability of fresh mixes was obtained using the flow table test that complies with the requirements of BS EN 1015-3, 1999 [44]. To determine the Total Water Absorption (TWA), cured specimens were placed in an electrical oven at 75°C until a constant weight was achieved. Thereafter, dried specimens were allowed to cool in a room (temperature of 20^{o}C), and the mass was later recorded to the nearest 0.1g. Dried samples were submerged in water until a constant weight was reached (weights were monitored at 24 hour intervals). Prior to measuring the mass of the saturated samples, excess water was removed using damp towels. Total Water Absorption was calculated using Equation 1, and the average of three specimens was recorded to the nearest 0.1%.

$$TWA = (m_s - m_d) * 100/m_d \qquad Equation\ 1$$

Where
TWA is Total Water Absorption %;
m_s is mass of saturated samples, in g;
m_d is mass of dried samples, in g.

Ultrasonic Pulse Velocity (UPV) was obtained by measuring the time requirements for an ultrasonic pulse to transmit through test specimens using Proceq Pundit Lab+ instrument. The average of three specimens (six sides) was recorded to the nearest 1m/sec. For the determination of compressive strength, the average of three cubes was recorded to the nearest 0.1 MPa. Mortar samples were tested in accordance to ASTM C109/C109M-02 [45] using SERCOMP7 hydraulic compressive strength machine with a loading rate of 2400 N/Sec. Length change due to drying shrinkage was obtained by attaching two pairs of demec-studs to the two sides of the prism that were cast against the steel mould (100mm between each stud). Demec-studs were attached immediately after demoulding using conventional super glue, and prisms were placed in a room (temperature of 20°C ± 2°C and a relative humidity of 50% ± 10%). Length change was monitored regularly using a digital dial gauge. The average reading of three specimens (6 sides) was calculated using Equation 2 and was recorded to the nearest 1 µ strain.

$$\varepsilon = (L_2 - L_1) * \ 10^6/L_1 \qquad Equation\ 2$$

Where
ε is strain, in Micro Strain;

L_2 is new length (new gauge reading), in mm;

L_1 is the original length (original gauge reading), in mm.

3 Results and discussion

3.1 Flowability

The flowability of the mortar mixes made using RSS or water and that also contained different amounts of u-FA is shown in Figure 3. The flowability of mortar reduced when the content of u-FA increased, and the lowest flowability of 113mm was recorded for the mortar mix with RSS and 30% u-FA (MR4). For the control mixes (Group 2), the flowability also decreased with the addition of u-FA and the lowest flowability of 115mm was recorded for the mortar mix with 30% u-FA (M4). The reduction in flowability may be due to the high unburned carbon content of the u-FA, which absorbs hydration water resulting in less workability [46-49]. The flowability of the mortar mixes with RSS was comparatively less than those for the mixes with water.

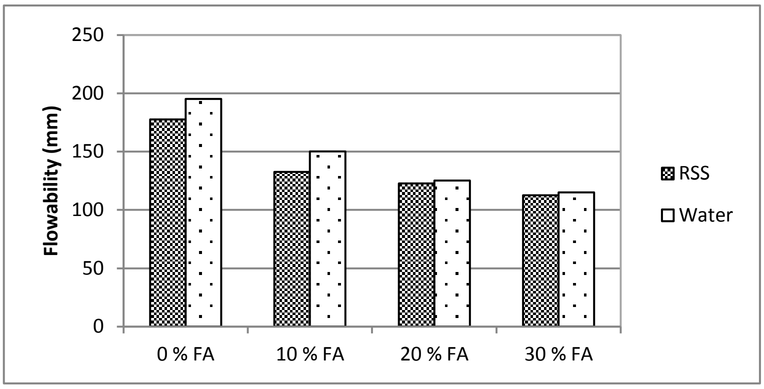

Figure 3: Flowability of mortar mixes with RSS or water.

3.2 Total Water Absorption (TWA)

The TWA for the mortar mixes with RSS is presented in Figure 4. The results showed that TWA decreased with curing age for all mixes up to 365 days, except for the mortar mix with 10% u-FA replacement. Figure 5 shows TWA results for the mortar mixes with water. The results generally showed that TWA decreased with curing age for all mixes, as TWA decreased with age up to 365 days. The irregularity in grading and particle shape of u-FA influences the water absorption properties by generating additional voids in the produced mortar. Water absorption properties also depend on the LOI values, which is directly associated with the amount of porous carbon contained in u-FA [46-49].

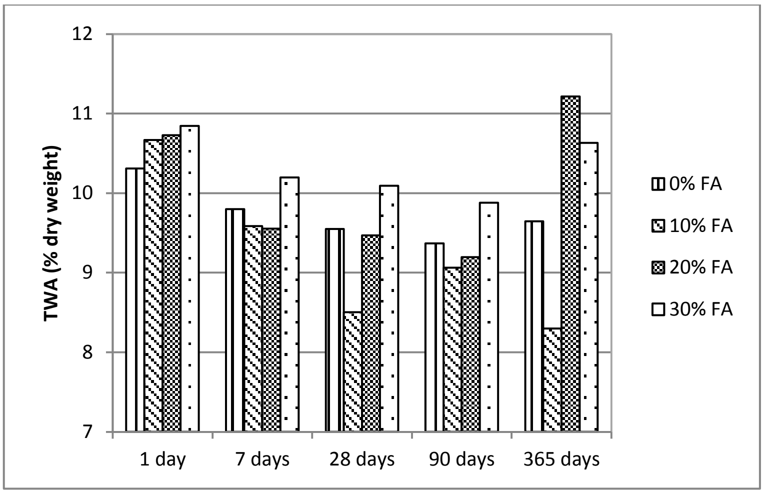

Figure 4: TWA for the mortar mixes with RSS and different u-FA content.

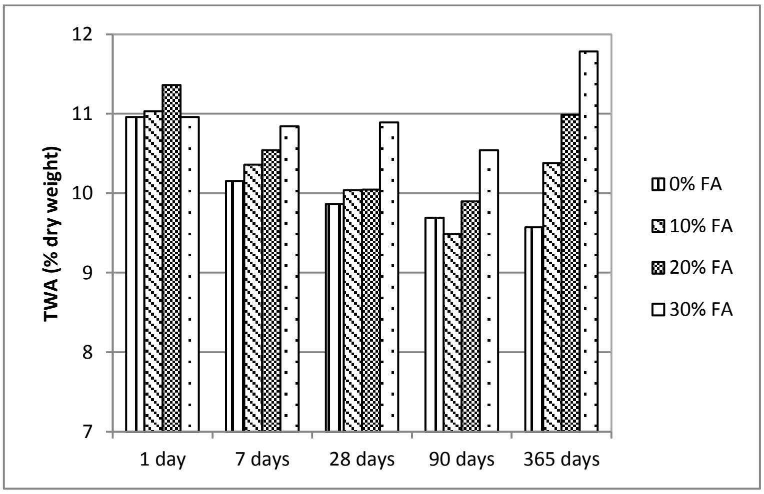

Figure 5: TWA for the mortar mixes with water and different u-FA content.

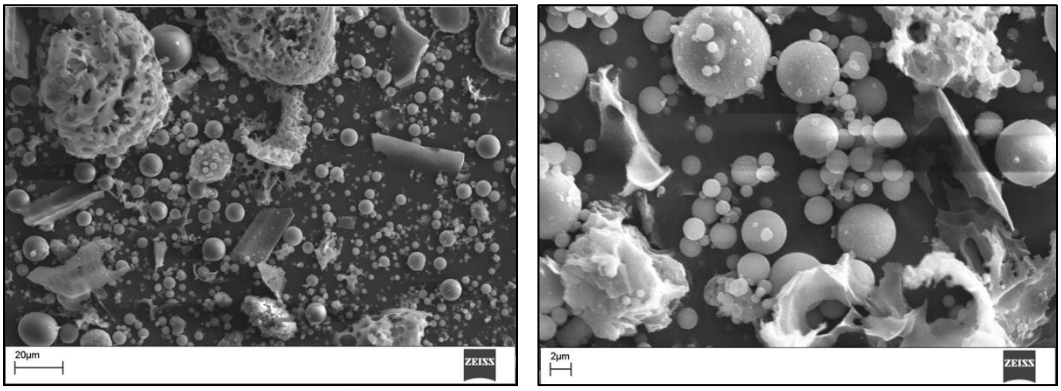

Figure 6: Images of u-FA using Scanning Electron Microscopes Technology (SEM).

3.3 Compressive strength

Figure 7 presents the compressive strength of the mortar mixes with RSS. At 1 and 7 days the compressive strength generally decreased when u-FA was included. At later ages, the result showed that the compressive strength improved when the content of u-FA increased, and the greatest compressive strength was recorded for the mortar mixes with 10 and 20% u-FA replacement. The results also showed that the addition of u-FA improved long-term strength, and prevented the decline in compressive strength observed for the mortar mix without u-FA at 365 days. The compressive strength for the mortar mixes with water is presented in Figure 8. The Figure showed that the compressive strength at 1, 7, 28 and 90 days decreased when u-FA content increased, and the greatest compressive strength was achieved for the mortar mix with 0% u-FA. At 365 days the results showed a significant improvement in the compressive strength for all mixes that contained u-FA, and the greatest compressive strength of 26.4 MPa was recorded for the mortar mix with 10% u-FA. This may be due to the positive impact of the pozzolanic activities of fly ash particles on long-term strength development [50-57]. The compressive strength of the mortar mixes with RSS was noticeably less than that of the mixes with water.

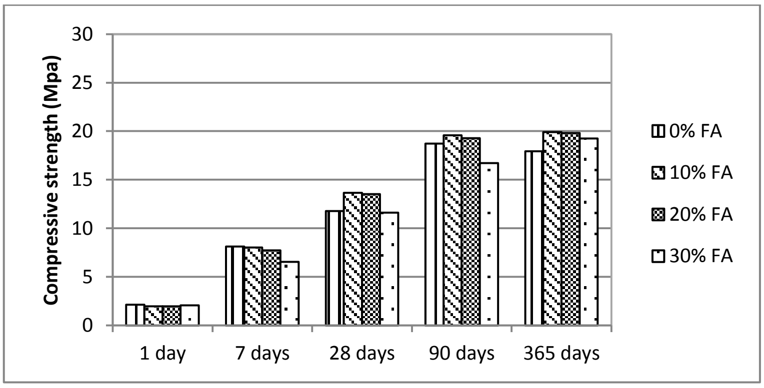

Figure 7: Compressive strength of mortar mixes with RSS and different u-FA content.

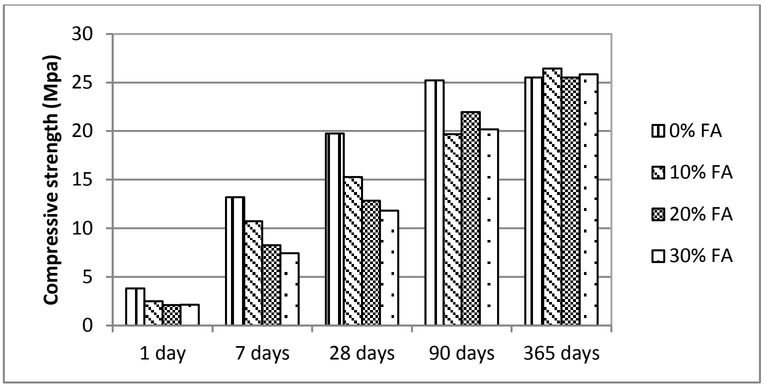

Figure 8: Compressive strength of mortar mixes with water and different u-FA content.

3.4 Ultrasonic Pulse Velocity (UPV)

The UPV of the mortar mixes with RSS is presented in Figure 9. The Figure shows that UPV values increased with curing age up to 90 days. It also shows that the UPV values at earlier ages (1 and 7 days) generally decreased when the content of u-FA increased. At later ages (28 and 90 days) no significant differences in UPV was observed, but some improvement in the UPV was noted at 365 days when u-FA was increased up to 20% replacement. It was also noted that the UPV values at 365 days were relatively less than those at 90 days, and this may be associated with degradation process of the organic component in RSS. The UPV of the mortar mixes with water is presented in Figure 10. The results showed that UPV values at 1, 7 and 28 days decreased when u-FA content increased and the greatest UPV readings were recorded for the mix with 0% u-FA. At later ages (90 and 365 days), the UPV values for the mortar mixes with u-FA were comparatively greater than those without, and the greatest UPV values were recorded at 365 days. The results also showed that UPV values continued to increase with time up to 365 days except for the mix with 0% u-FA (an anomalous result). This may be associated with the long-term strength development that resulted from the inclusion of fly ash [50-53]. The UPV of the mortar mixes with water was generally higher than that of the mixes with RSS (except at 1 day for the mixes with 20 and 30%).

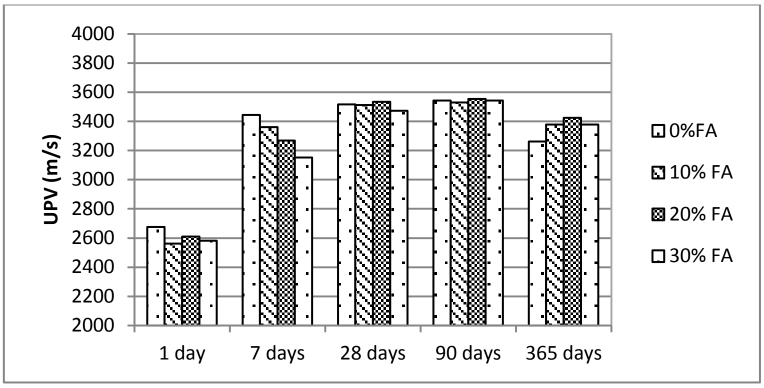

Figure 9: UPV of the mortar mixes with RSS and different u-FA content.

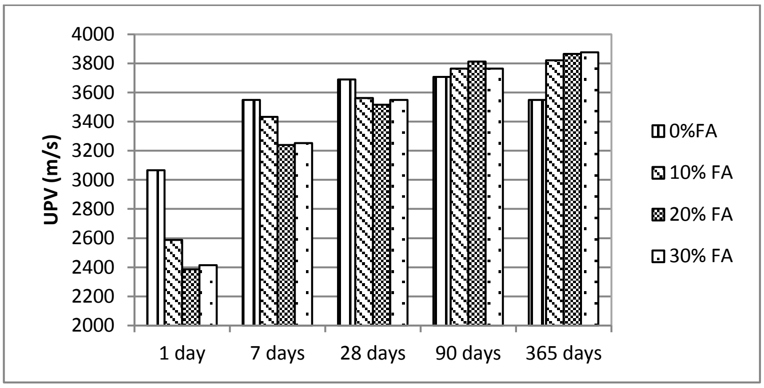

Figure 10: UPV of the mortar mixes with water and different u-FA content.

3.5 Correlation

The relationship between the compressive strength and UPV is shown in Figure 11. The Figure demonstrates a strong correlation between these two properties, and Equation 3 has been developed to predict the compressive strength by using the non-destructive readings of the UPV test.

$$y = 0.01582e^{0.00194x} \qquad Equation\ 3$$

<u>*Where:*</u>

y is UPV in m/s, and *x* is compressive strength in MPa

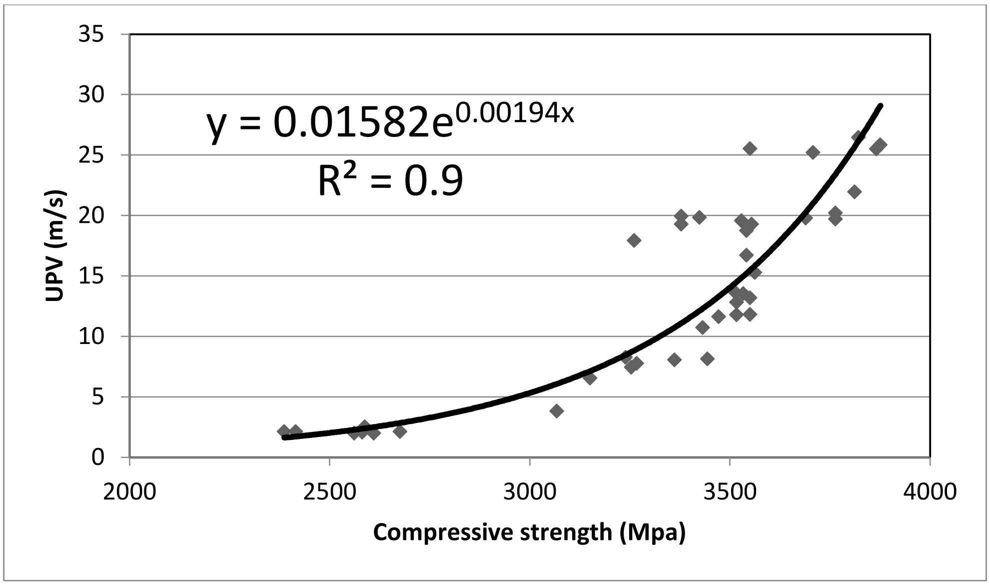

Figure 11: Correlation between compressive strength and UPV.

3.6 Length change

The length change of the mortar mixes with RSS and water is shown in Figure 12 and Figure 13 respectively. The results clearly showed that drying shrinkage decreased when u-FA content increased, and the best results were observed when 30% u-FA was added. Moreover, the drying shrinkage mostly occurred during the first 50-70 days, through which no significant impact of the inclusion of u-FA on drying shrinkage was noted. The mixes with RSS demonstrated less drying shrinkage in comparison to those made with water.

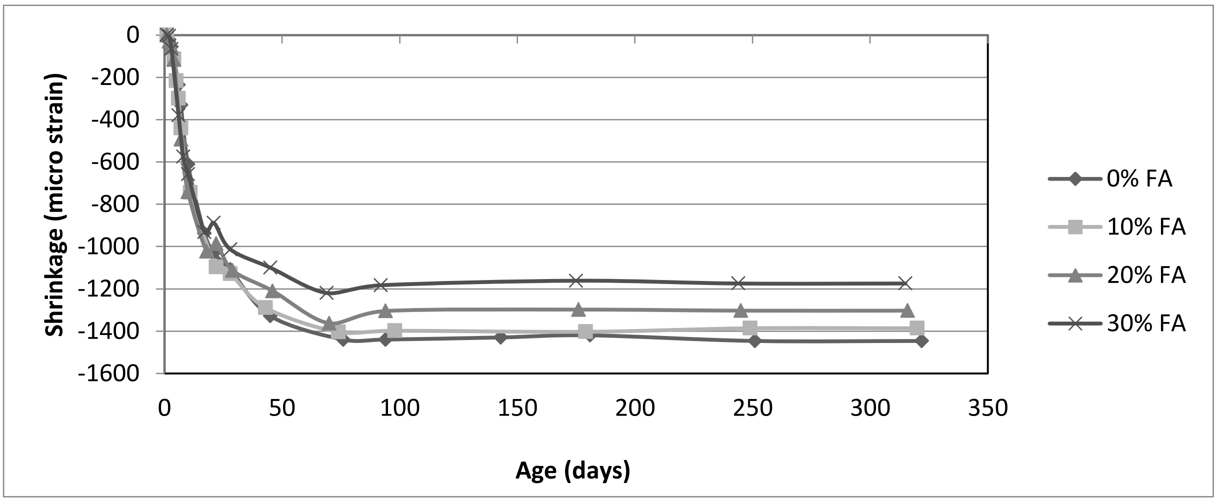

Figure 12: Shrinkage of the mortar mixes with RSS and different u-FA content.

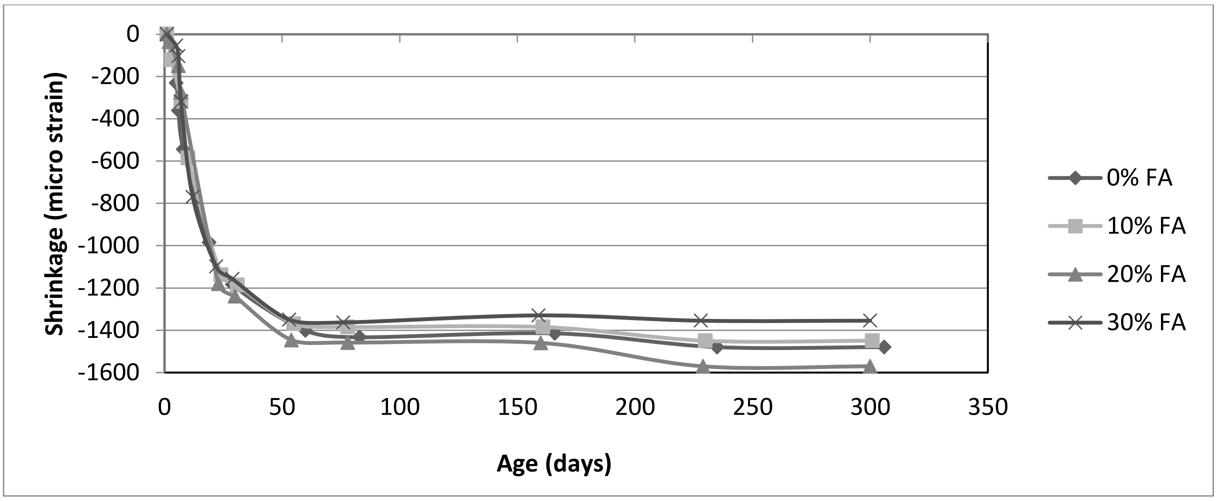

Figure 13: Shrinkage of the mortar mixes with water and different u-FA content.

4 Conclusions

- The addition of u-FA significantly reduced flowability for the mortar mixes with both RSS and water. The flowability of the mortar mixes with RSS was comparatively less than those with water.
- For the mortar mixes with RSS and water, TWA generally increased with the inclusion of u-FA. The TWA of the mortar mixes with RSS was comparatively less than those with water.
- For the mortar mixes with u-FA and RSS, the UPV values generally decreased with the inclusion of u-FA at all curing ages. For the mortar mixes with water, the UPV values at 1, 7 and 28 days decreased when the u-FA content increased and the greatest UPV readings were recorded for the mortar mix with 0% u-FA. At 90 and 365 days, UPV increased with the inclusion of u-FA. UPV values of the mortar mixes with RSS were comparatively less than those for the mixes with water.
- For the mortar mixes that contained u-FA and RSS, the results showed that the inclusion of 10-20% u-FA improved compressive strength at 28, 90 and 365 days. The results also showed that the addition of u-FA improved long-term strength, and prevented the decline in compressive strength observed for the mortar mix with RSS

and 0% u-FA at 365 days. For the mortar mixes with water, the compressive strength at 1, 7, 28 and 90 day decreased when u-FA was included. However, the inclusion of 10% u-FA improved long-term compressive strength. Moreover, the compressive strength of the mortar mixes with RSS was noticeably less than that of the mixes with water.

- The addition of u-FA reduced drying shrinkage for the mortar mixes with both RSS and water.

5 Benefits and practical applications

In addition to the production of sustainable construction materials, the outcome of utilising sewage products in the construction industry could see huge financial savings to the current economical constraints by eliminating the costly processes involved in treating these wastes. This would also lead to a huge reduction in energy consumption. Furthermore, there are huge environmental benefits from the prevention of RSS transportation to landfills and incinerators. Using RSS as a water replacement in mortar or concrete mixes may provide an opportunity to reduce the great demand on freshwater due to the continuous and unsustainable growth in the world population.

Cement-based materials containing RSS and u-FA can be used in different construction and civil engineering applications, and as follows:

- Masonry mortar for external applications
- In-situ concrete for external applications
- Precast units for external applications
- Self-compacting concrete
- Cement-based materials for road construction

6 Acknowledgement

The authors would like to thank the University of Wolverhampton for funding this research. The authors would like to acknowledge the support of the technical staff in the construction and environmental laboratories, Mr G. Cooper, Mr R. Bradley, Mrs D. Spencer and Mr D. Townrow - School of Architecture and Built Environment, Faculty of Science and Engineering, University of Wolverhampton.

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