- Technical Paper -

UTILIZING WASTE AND RECYCLED MATERIALS IN FLY ASH FIBER-REINFORCED MORTAR

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ABSTRACT

This experimental investigation was conducted to determine the effect of fiber type and mixing proportion on the strength and durability of fiber-reinforced mortar with fly ash. The compressive strength was not significantly affected by sand-binder ratio, but flexural strength increased as sand-binder ratio increased. Increasing the volume of fly ash resulted in a decrease in compressive and flexural strength, flexural toughness, and air permeability, but this result may be attributed to the slow curing speed of fly ash. Polypropylene and recycled fiber mortars exhibited similar behavior.

Keywords: sustainability, polypropylene fibers, recycled fibers, fly ash, strength, durability

1. INTRODUCTION

The essence of sustainable development is the “triple bottom line” of balance between environmental, economic, and social well-being. The development of new concrete materials needs to consider these criteria as another important performance metric; just as strength or durability are measured and used to evaluate the applicability of a given concrete, so too should a concrete material be designed for environmental friendliness, social benefit, or reduced economic cost. A framework for developing sustainable concrete materials, such as that in Figure 1, can be a helpful tool for creating design information which combines engineering knowledge with sustainable criteria, and for applying that design information to create “green” concretes by utilizing materials which meet sustainable criteria [1].

Of those three criteria, the environmental aspect is arguably the most widely known; climate change and the generation of greenhouse gases (GHG) is an international topic. The Intergovernmental Panel on Climate Change stated in 2007 that efforts to mitigate GHG emissions in the near future can have long-term benefits for reducing the effects of climate change [2].

Carbon dioxide (CO_2) is the primary GHG contributing to climate change, and the concrete industry is a major generator of CO_2, with some researchers estimating that the production of Portland cement is responsible for roughly 7% of the world’s total emissions [3]. In addition, the production of concrete consumes large amounts of natural resources. Therefore, the environmental challenge to the concrete industry is to reduce CO_2 emissions and optimize the usage of alternative products to reduce the consumption of virgin materials.

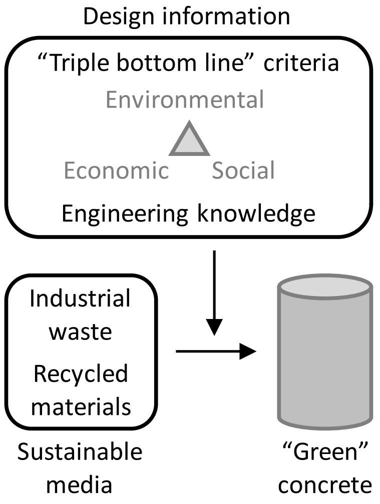

Fig.1 Framework for developing sustainable concrete materials

A durable concrete which replaces virgin materials with industrial waste or recycled products could provide a sustainable option for construction materials. Fly ash, a waste by-product of the coal industry, has been used to replace up to 70% of Portland cement in some concretes [3]. The combination of high-volume fly ash and polypropylene fibers has been investigated in shotcrete applications, where it was found that satisfactory fresh and hardened properties could be achieved [4]. Fibers made from recycled plastics have also been successfully applied in concrete [5]. These applications demonstrate the different possibilities which exist for utilizing alternative materials to develop sustainable concrete.

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In this paper, fly ash mortar reinforced with polypropylene and recycled fibers was tested for strength and durability at different mix proportions. The end goal of this research work is to investigate the potential of high-volume fly ash, fiber-reinforced concrete with recycled aggregates, but it is first necessary to determine the mix proportion which best combines these materials at the mortar level before introducing recycled aggregates to the matrix. The investigation was carried out in two stages. First, the sand-binder ratio was varied while holding other variables constant. Different fiber types and fly ash volumes were then introduced in order to understand their effect on performance. Finally, the CO_2 emissions of the mortar mixes was calculated.

2. EXPERIMENTAL PROGRAM

2.1 Materials

Cement mortar was prepared using tap water (W), Type 1 Portland cement (C), river sand (S), fly ash (FA), polypropylene (PP) or recycled fibers, and air entraining (AE) and super plasticizer (SP) admixtures.

The fly ash used was type JIS II fly ash, which met requirements specified by JIS A 6201.

Fiber properties are given in Table 1. The recycled fibers were manufactured from recycled polyethylene terephthalate (PET).

2.2 Mix proportions

Mortar mix proportions are given in Table 2. The term binder (B) is used to represent all cementitious materials – in this case, fly ash and Portland cement. All mixes used a constant water-binder ratio of 30%.

To investigate the effect of sand-binder ratio, a constant fly ash-binder ratio of 30% was used with PP fibers at 2% volume, and three sand-binder ratios of 60%, 80%, and 100% were chosen. For investigating the effect of fiber type and fly ash-binder ratio, mortar mixtures containing either PP or recycled fibers at 2% volume were mixed at a constant sand-binder ratio of 80% with three fly ash-binder ratios of 30%, 50%, and 70%. AE and SP were varied as necessary to maintain satisfactory fresh mortar properties.

2.3 Mixing & casting

Mixing for the first stage was performed in two batches in a 25 L mixer. Water, cement, and fly ash were mixed first, then sand was added, and finally the fibers were added gradually. Stage two specimens were mixed in a 75 L mixer in one batch. First sand, then cement and fly ash were added and mixed, then water was added. After that, the fibers were gradually added.

Cylinder (10Ø×20cm) and beam (10×10×40cm) specimens were cast for each concrete mix following JSCE-F 552-1999. Cylinder specimens were cast in two layers and beam specimens in one layer, with a vibrator applied to the outside of the mold after each layer was placed. After casting, molded specimens were covered in plastic wrap and cured in the molds for 24 hours, after which they were removed from the molds and moved to water curing. Testing was conducted 28 days after casting.

2.4 Fresh mortar properties

The properties of fresh mortar are given in Table 3. The slump flow test was conducted according to JIS A 1150; efflux time (flowability) was measured according to JSCE-F 512-1999; and air content was measured according to JIS A 1116.

Table 1 Fiber properties

Type	Dia. (mm)	Length (mm)	Density (g/cm^3)	Strength (MPa)
PP	0.75	32	0.91	-
Recycled	0.70	30	1.35	450

Table 3 Fresh mortar properties

Series	Slump flow (mm)	Efflux time (s)	Air content (%)
SB60	495	6.5	-
SB80	495	5.7	-
SB100	585	5.7	-
FA30-PP	600	4.7	11.6
FA50-PP	360	10.7	12.1
FA70-PP	650	4.4	9.1
FA30-RF	595	5.5	9.9
FA50-RF	415	6.7	11.6
FA70-RF	660	4.6	8.6

Table 2 Mortar mix proportions

Series	Material ratios (%)			Mix proportions (kg/m^3)				Admixtures (%binder)		Fibers (%volume)	
	W/B	S/B	FA/B	W	C	FA	S	AE	SP	PP	Recycled
SB60	30	60	30	298	695	298	596	0.04	0.4	2.0	-
SB80	30	80	30	274	639	274	731	0.04	0.5	2.0	-
SB100	30	100	30	254	593	254	847	0.04	0.6	2.0	-
FA30-PP	30	80	30	274	639	274	731	0.04	0.5	2.0	-
FA50-PP	30	80	50	266	443	443	709	0.06	0.4	2.0	-
FA70-PP	30	80	70	259	259	604	691	0.08	0.4	2.0	-
FA30-RF	30	80	30	274	639	274	731	0.04	0.5	-	2.0
FA50-RF	30	80	50	266	443	443	709	0.06	0.4	-	2.0
FA70-RF	30	80	70	259	259	604	691	0.08	0.4	-	2.0

2.5 Specimen testing

Four properties of the mortar mixes were tested experimentally. Compressive strength f_c was measured according to JIS A 1108-2006, and flexural strength f_b and flexural toughness f_t were determined according to JSCE-G 552-1999. For all tests, reported values are the average of three specimens.

Air permeability K was measured as follows. Air permeability specimens were taken from cylinders by cutting a 40 millimeter-thick section from the center of the cylinder. Specimens were then placed in a drying machine for one week at 40°C and checked by monitoring the weight change. After dry conditions were met, the specimens were set into an air permeability machine and the volume of air flow was measured under steady state conditions. The air permeability coefficient was calculated per Eq. 1.

$$K = \frac{2P_2 \cdot h \cdot r}{P_1^2 - P_2^2} \cdot \frac{Q}{A} \quad (1)$$

where,
K : air permeability coefficient (mm/s)
P_1 : loading pressure (MPa)
P_2 : atmospheric pressure (MPa)
h : specimen thickness (mm)
r : unit volume weight of air (1.205×10^{-6} MPa)
Q : air flow volume (mm^2/s)
A : sectional area (mm_2)

3. EXPERIMENTAL RESULTS

A summary of all experimental results is given in Table 4. Figure 2 shows results for variable sand-binder ratio, and Figure 3 shows results for specimens with variable fiber type and fly ash-binder ratio.

4. DISCUSSION

4.1 Effect of sand-binder ratio

Compressive strength, flexural strength, and flexural toughness results are shown in Figures 2a, 2b, and 2c, respectively. From Figure 2a, it can be seen that increasing the sand-binder ratio resulted in a marginal decrease in compressive strength; from 60% to 80% the compressive strength decreased 1.4 MPa, and from 80% to 100% the decrease was 4 MPa.

The effect of sand-binder ratio is more pronounced for flexural strength and toughness. Figures 2b and 2c show that increasing the sand-binder ratio from 60% to 80% and from 80% to 100% resulted in flexural strength increases of 1.91 MPa and 0.54 MPa, respectively; flexural toughness increased 1.35 MPa and 0.37 MPa, respectively.

From these results, a sand-binder ratio of 80% is considered optimal, as it produces the best combination of compressive strength and flexural performance. A sand-binder ratio of 60% has slightly higher compressive strength but much lower flexural strength and toughness values, whereas a sand-binder ratio of 100% produces the highest flexural performance but with a much lower compressive strength value.

Table 4 Summary of experimental results

Series	f_c (MPa)	f_b (MPa)	f_t (MPa)	$K \times 10^{-12}$ (mm/s)
SB60	55.2	5.70	4.56	-
SB80	53.8	7.61	5.91	-
SB100	49.8	8.15	6.28	-
FA30-PP	45.3	7.30	5.83	1.73
FA50-PP	33.3	4.57	3.82	1.66
FA70-PP	18.9	4.24	3.65	12.40
FA30-RF	49.1	6.94	5.15	2.90
FA50-RF	35.0	4.57	4.17	1.75
FA70-RF	19.9	4.87	3.81	8.59

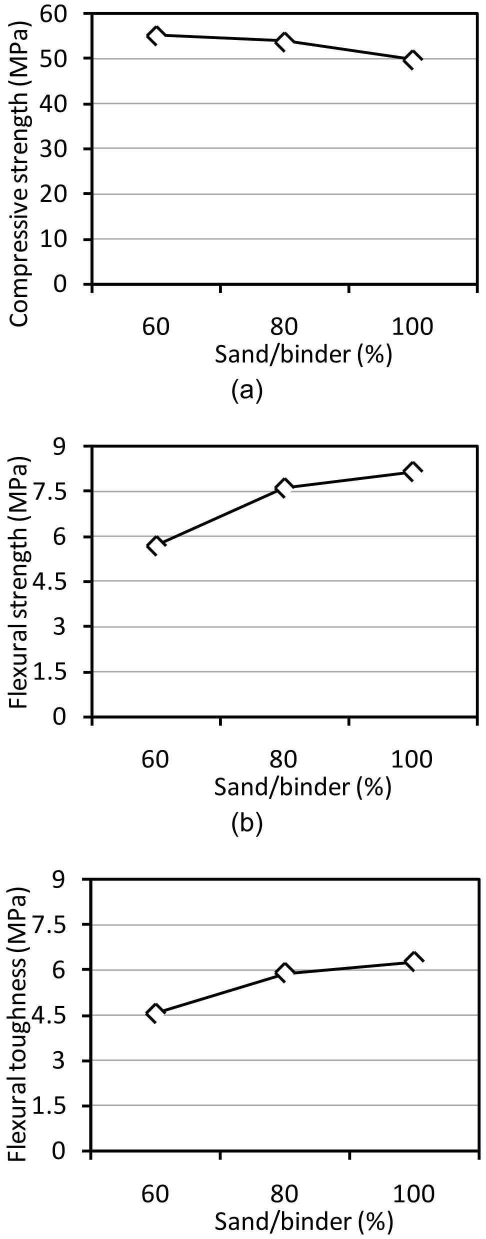
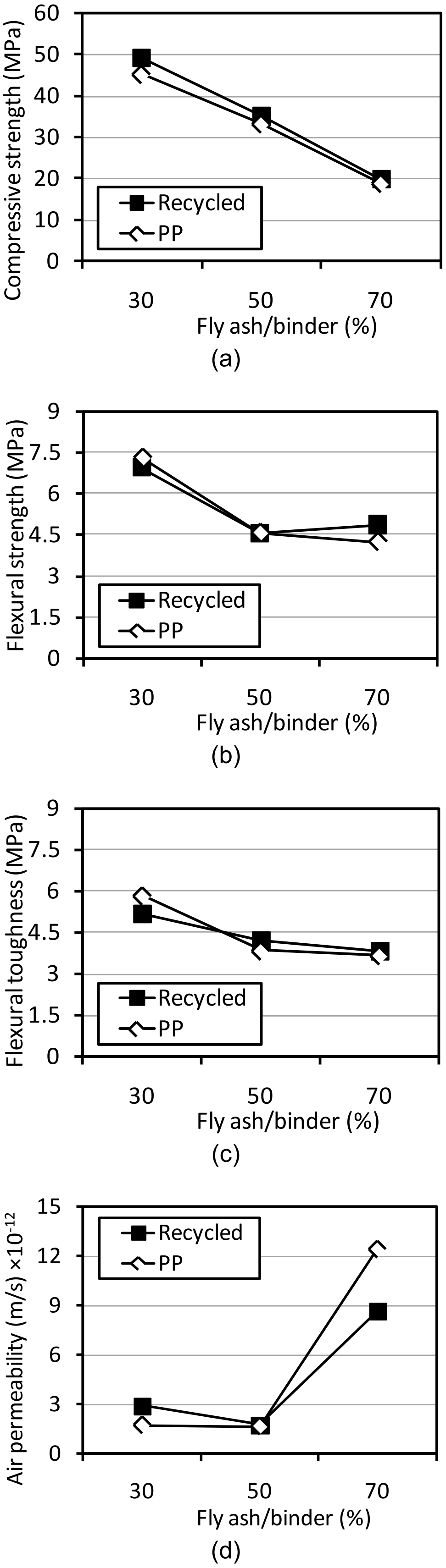


Fig.2 (a) Compressive strength, (b) flexural strength, and (c) flexural toughness for variable sand-binder ratio



(a)

(b)

(c)

(d)

Fig.3 (a) Compressive strength, (b) flexural strength, (c) flexural toughness, and (d) air permeability for variable fly ash-binder ratio

4.2 Effect of fly ash-binder ratio

Compressive strength, flexural strength, flexural toughness, and air permeability results are shown in Figures 3a through 3d, respectively. In Figure 3a, it can be seen that the compressive strength decreases constantly for increasing fly ash-binder ratio; from 30% to 50% the compressive strength decreased by 12 MPa and 14.1 MPa for PP and recycled fibers, respectively, and from 50% to 70% it decreased by 14.4 MPa and 15.1 MPa for PP and recycled fibers, respectively.

The effect of fly ash-binder ratio on flexural performance was different from that on compressive strength at higher ratio values, as seen in Figures 3b and 3c. An increase in fly ash-binder ratio from 30% to 50% was accompanied by a 2.73 MPa and 1.41 MPa decrease in flexural strength for PP and recycled fiber specimens, respectively, and by a 2.01 MPa and 0.98 MPa decrease in flexural toughness for PP and recycled fiber specimens, respectively. However, increasing the fly ash-binder ratio from 50% to 70% resulted in a much smaller decrease of 0.33 MPa and a small increase of 0.30 MPa in flexural strength of PP and recycled fiber specimens, respectively, as well as small decreases of 0.17 MPa and 0.36 MPa in flexural toughness of PP and recycled fiber specimens, respectively.

In Figure 3d, the effect of higher fly ash-binder ratio is more apparent, as the air permeability increased 10.74×10^{-12} m/s for PP and 6.84×10^{-12} m/s for recycled fibers from 50% to 70%. In contrast, the change in air permeability was much lower when increasing from 30% to 50% - 0.07×10^{-12} m/s and 1.15×10^{-12} m/s decreases for PP and recycled fibers, respectively.

From these results, it can be seen that a higher volume of fly ash results in decreased strength and durability characteristics. However, it is important to note that these tests have been performed after 28 days of curing. While the behavior of plain cement mortar at 28 days can be assumed to be reflective of its overall behavior, fly ash requires a much longer curing period in order to realize its performance benefits. Since the fly ash reaction is delayed, the amount of cementitious reaction which has occurred by 28 days will be far less for mortars containing higher volumes of fly ash. This effect can be clearly seen in the air permeability results, as there is a sharp increase in air permeability when increasing the fly ash-binder ratio to 70%. Specimens have already been prepared for testing at 6 months and 1 year, and these results should give a better indication of the capability of high-volume fly ash replacement.

4.3 Effect of fiber type

Both PP and recycled fiber results are shown in Figures 3a through 3d. From these figures, and as discussed above, it can be seen that fiber type does not have a significant effect on any of the strength properties measured. In the case of durability, it is difficult to interpret the air permeability results at this time due to the delayed reaction of fly ash, but as air permeability typically evaluates the cement paste, no significant difference is expected to occur.

5. ENVIRONMENTAL ASSESSMENT

5.1 Life cycle assessment

Life cycle assessment (LCA) is a tool which has been developed for evaluating environmental impact. LCA is used to study a product’s effect on the environment throughout its service period, which for concrete construction encompasses six phases, illustrated in Figure 4.

In this research, the development of a new material is the primary interest, so the full life-cycle details are not yet decided. Therefore, to simplify the LCA, only the first two steps of the material flow will be used for calculating the environmental impact of the mortar mixes. Since these boundary conditions no longer encompass a full “life-cycle,” the term environmental assessment will be used to describe this evaluation.

5.2 Environmental impact metrics

Two criteria are typically used for evaluating environmental impact of concrete: energy consumption and GHG emissions. This paper focuses on GHG emissions – specifically, CO_2 emissions. While other gases are known to contribute to climate change, such as methane and nitrous oxide, CO_2 dominates the contribution to climate change even though its global warming potential is lower than the other two gases.

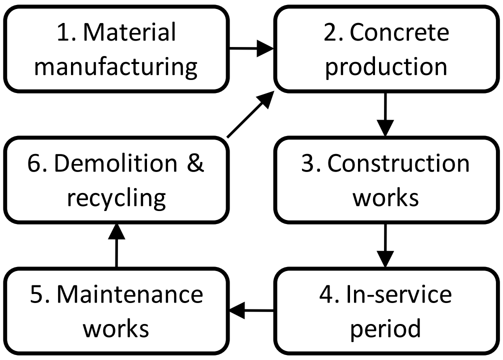


Fig.4 Material flow for concrete construction [6]

5.3 Life cycle inventory

The life cycle inventory is a database which contains the emissions, energy consumption, and other data related to the manufacturing of concrete and its constituent parts. In this research, only the contributions from Portland cement, sand, and fly ash will be considered. The chemical admixtures make up an extremely small fraction of the total volume, and there is insufficient data regarding the production of the fibers; furthermore, the three main components (cement, sand, and fly ash) constitute nearly the entire volume of the mortar matrix, so the other components will be disregarded. CO_2 emissions for the set boundary condition for each of the primary components are given in Table 5.

5.4 Evaluation and discussion

The CO_2 emissions for the mortar mixes are calculated by multiplying the contribution of each component by its mixing proportion, which is given in Table 2. A summary of the emissions per mortar mix is given in Table 6 and shown in Figure 5.

Table 5 CO_2 emissions by material [6]

Material	CO2 released (kg CO_2/ton)
Portland cement	765.5
Natural river sand	3.4
Fly ash	17.9

Table 6 Summary of mortar mix CO_2 emissions

Series	Material (kg CO_2/m^3)			Total (kg CO_2/m^3)
	C	FA	S	
SB60	532.0	5.3	2.0	539.4
SB80	489.2	4.9	2.5	496.5
SB100	453.9	4.5	2.9	461.4
FA30-PP	489.2	4.9	2.5	496.5
FA50-PP	339.1	7.9	2.4	349.5
FA70-PP	198.3	10.8	2.3	211.4
FA30-RF	489.2	4.9	2.5	496.5
FA50-RF	339.1	7.9	2.4	349.5
FA70-RF	198.3	10.8	2.3	211.4

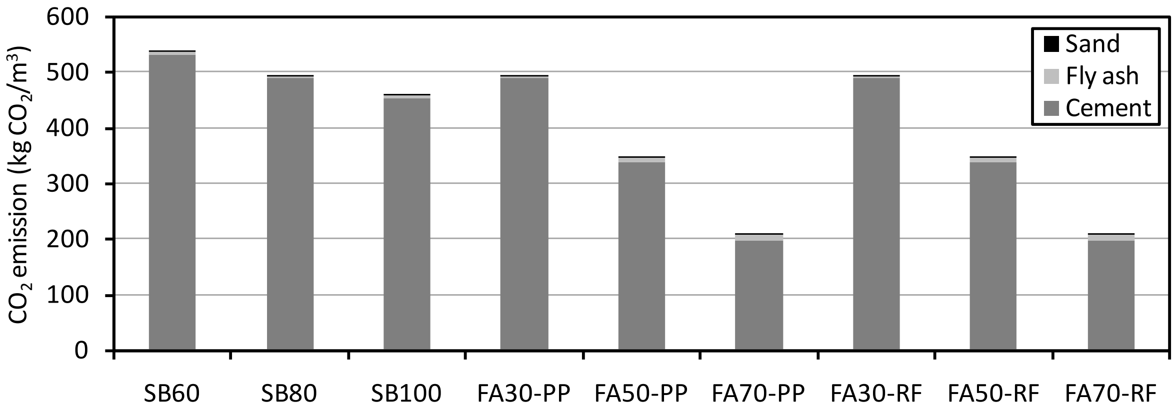


Fig.5 CO_2 emissions per cubic meter of mortar by series

From Figure 5, it can be clearly seen that Portland cement contributes the largest amount of CO_2 emissions per mixtures. In the mixes with the highest CO_2, such as SB60, Portland cement contributes nearly 99% of the total emissions; in the mixes with the lowest CO_2, such as FA70-PP, it still contributes nearly 95%. While the percentage contribution of Portland cement does not decrease significantly, the total CO_2 of the mix does, with the FA70-PP mix releasing just less than 40% of the SB60 mix. The value of fly ash replacement for reducing CO_2 is therefore clear, as a large savings in emissions can be realized by replacing the largest emitter of GHG with another material with a much smaller impact.

6. CONCLUSION & FURTHER RESEARCH

In this paper, the effect of mixing proportions, such as the sand-binder ratio and the fly ash-binder ratio, and fiber type on strength and durability properties of fly ash fiber-reinforced mortar was investigated. From the experimental results, the followings conclusions were made.

(1) A sand-binder ratio of 80% provided the best balance between compressive and flexural behavior. Decreasing the sand-binder ratio produced slightly higher compressive strength but lower flexural strength, whereas increasing the sand-binder ratio reduced compressive strength but slightly increased flexural strength.

(2) Increasing the fly ash-binder ratio from 30% to 70% resulted in lower strength and durability properties. While the compressive strength decreased constantly, the flexural strength only slightly decreased when changing from 50% to 70%. Conversely, air permeability underwent a huge increase when moving from 50% to 70%.

(3) The decreased performance of higher-volume fly ash mortars may be attributed to the slow reaction speed of fly ash, which requires longer curing before full performance can be achieved.

(4) There was no observed significant difference in the performance between polypropylene and recycled fiber-reinforced mortars.

(5) Portland cement is the primary contributor of CO_2 emissions in the mortar mixes. While replacing cement with fly ash at a fly ash-binder ratio up to 70% does not decrease the fraction contribution of cement, it can help reduce total CO_2 emission of the mortar mixture by over 60%.

(6) At this time it is difficult to fully determine the contribution of recycled materials such as recycled fibers to CO_2 emissions or other environmental measurements. However, the usage of such materials has an inherent positive benefit to society, so appropriate methods for evaluating this benefit need to be developed.

(7) Future research works will first address the issue of delayed fly ash reaction by testing specimens at 6 months and 1 year. Results from these tests should be more indicative of the comparative performance of high-volume fly ash mortar. Recycled aggregates will then be introduced into the matrix, and the effect of different volumes on both the mechanical performance, such as strength and durability, as well as the environmental impact will be evaluated.

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