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Utilizing Local Waste Materials to Produce Eco-friendly, Thermally Resistant Concrete

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ABSTRACT

Tires rubber waste (RW) accumulate as the population grows and demand for vehicles increases. As concrete plants are erected, more cement is made, releasing hazardous gases. The fly ash (FA) accumulation from power stations has increased, so experts must find solutions to address these challenges. In the current study, cement was replaced by 25%, 30%, and 35% FA. Silica fume (SF) was used at 10% of the cement weight to prevent FA from reducing concrete strength. A part of the specimens was subjected to temperatures of 400℃ and 800℃ to study the response of the specimens to heat. The combination contained 0.5% RW of the fine aggregate weight to prevent the specimens from spalling. The splitting tensile strength (STS) test was employed to examine the mechanical strength, while the ultrasonic pulse velocity (UPV) test was incorporated to validate the results of the mechanical characteristics behavior. An investigation was conducted to examine the impact of elevated temperatures on the weight and surface color of the concrete specimen. The combined 30% FA with 10% SF and 0.5% RW enhanced the STS by 32% at normal temperature and 56.6% at 400℃, while the UPV readings remained in the rank (good) until 400℃ for the same specimen. While the 800℃ significantly reduced the quality of all mixes, including the specimen weights. The color changes of the specimen were clearly explained. The findings suggested that the FA and RW materials could be used in concrete to preserve the environment as cleanly as possible.

1. INTRODUCTION

Recent decades have seen a global rise in normal and high-strength concrete (HSC). These concretes have better physical and mechanical qualities due to silica fume (SF), nano-silica (NS), nano clay, and nano pozzolanic additives. Using alternative materials in concrete reduces society's environmental impact. Polyethylene terephthalate (PET), polypropylene (PP), and rubber (RW), fly ash (FA), rice husk, eggshell, glass, and aluminum or iron wastes can replace natural aggregates and cement [1-16]. Unlike steel, HSC is brittle and has low tensile strength, according to various studies. This trait causes designers problems, especially when using the concrete in high-rise buildings [2, 3, 5, 17, 18]. Another significant issue that threatens the strength of concrete is fire. Multiple research studies have demonstrated that HSC has a much greater susceptibility to heat than NC. In general, concrete disintegrates poorly at 400- 1000℃, denser concrete is more heat-sensitive to cracking and spalling at these temperatures [3, 19].

Increasing population drives automobile demand, which boosts rubber tire production. Single-use plastic from food and pharmaceutical packing and injured tire rubber pose health and safety risks and require timely, sustainable disposal [5]. About half of the one billion tires that reach the end of their lifespan are recycled, while the rest end up in landfills [20]. Soil burial harms plant growth, and ocean and sea removal deplete fish resources. Burning releases harmful gasses [3, 5, 21].

Numerous researchers have attempted to develop environmentally friendly methods of waste disposal, such as shredding the waste into granules of varying sizes, stripping it to varying thicknesses and lengths, and incorporating it into concrete mixtures in varying proportions or quantities. Rubber waste (RW) at 1-3% of the fine aggregate volume and particle size 0.25-1 mm reduced compressive, flexural, and splitting tensile strengths by 24%, 22%, and 20.5%, respectively, in HSC. In addition, specimens with a higher proportion and size of granules had a lower ultrasonic pulse velocity (UPV) reading; confirming the accuracy of the lacking strength results, the quantity of RW particles was more important than their size [22]. Utilizing coarse RW aggregate with a particle size of 2-38 mm instead of 25% natural aggregate in concrete reduced splitting tensile strength by 36%. The reduction was 75% after replacing natural aggregate with 100% RW [23]. The fine aggregate was replaced at 5, 10, 15, and 20% ratios to explore how RW affects concrete strength. As the replacement ratio increased, compressive and splitting tensile strengths decreased. Based on energy absorption studies, specimens with 15% RW replacement exhibit the highest impact toughness [24]. Specimens containing RW granules showed significant reduction in flexural, compressive, and splitting tensile strengths. Replacement ratios below 50% reduce strength most significantly. Rubberized lightweight aggregate concrete mixtures improve flexibility due to lower static modulus of elasticity [25].

Global concrete production is highest in China. China cement production was 2.15 billion tons in 2012, followed by India at 8.6% and the USA at 29% [26, 27]. In July 2020, Malaysia manufactured 1,866 thousand tons of cement [28]. Cement manufacture, shipping, silo loading, and unloading pollute dust [29]. Each ton of cement produced results in the production of approximately another ton of global greenhouse gas (GHG). Nitrogen oxides (NO_X) are one of these pollutants, as each ton of cement clinker emits 1.5 kg to 10 kg of this gas into the atmosphere [30]. NO_X comes from fuel, nitric acid, and biomass burning. Dust and air pollution harm worldwide health and lifestyle [31]. CO_2 will be emitted along with water vapour at high temperatures during the synthesis of CaO in the production of cement [32]. It generates 5% to 7% of global CO_2 emissions from total industrial energy consumption [33, 34]. Cement manufacturing generates noise from raw material preparation, storage, clinker burning, and heavy equipment operation. Cement facilities produce gas dynamic noise from blowers, mechanical noise from machines and crushers, and electromagnetic noise from electric engines [35]. Noise pollution harms the heart, brain, and gut. Neurasthenia syndrome-cognitive impairment, elevated blood pressure, insomnia, vertigo, cephalalgia, and fatigue is more common among cement plant workers exposed to noise [28, 36].

Most nations' coal power facilities emit significant FA. Humans and the environment are harmed by it. China produced 550 million tons of coal fly ash (CFA) in 2018, but inadequate use brought the total to above 3 million tons [37]. Heavy metal FA dispersion as fine particle matter is wind-transported. Soil, air, and water pollution are endangered. FA is a sophisticated mixture of ingredients that makes it an environmentally friendly concrete cement substitute. FA comprises C, S, O, Si, Mg, Fe, Al, K, Na, Ca, Ti, Hg, As, Cr, Pb, Cd, Cu, Mo, Ba, Ni, B, and Zn [38]. Chinese government promote CFA resources. Paving, mine backfilling, concrete, cement, and low-end building materials contribute 56% of CFA [39]. Since the 1950s, CFA has been the best concrete adding method worldwide. Chemically similar to Portland cement, CFA has pozzolanic solid action [40, 41].

Previous research has shown that replacing cement with 0, 5, 10, and 15% FA reduced the strength, while adding 15% SF enhanced mechanical strength, especially for specimen with 10% FA and 15% SF [42]. For mixes containing up to 20% RW of fine aggregate, the SF was included to strengthen the expected reduction in strength. RW and SF demonstrated considerable coupling effects on mix fracture performance. Replacing of 10% cement with SF reduced rubber's negative effects better than 3%. Mechanically, the mix improved with presence of 5% RW and 10% SF which produced concrete more environmentally and friendly than traditional concrete [43]. FA at 50, 60, and 70% weakened concrete. Most decreased by 66% at 70% FA. While the inclusion of 10% and 20% SF produced hardened concrete. At 400℃, SF and FA concrete outperformed standard concrete. From 600℃ to 1000℃, all combinations weakened [44]. Replacing cement with 30, 35, and 40% FA decreased compressive, flexural, and splitting tensile strength. Heat specimens contain 5% SF to 400℃ enhanced strengths. All specimens weakened at 700℃ [5]. Even at 700℃, NS and FA exhibited better residual strength than the reference [2].

The research above shows that solid waste, especially rubber, hurts the ecosystem. Environmentally hazardous gases originate from cement combustion. As an alternative to cement or natural aggregates, concrete with substantial amounts of waste like FA and RW has weak mechanical properties. This study aims to produce eco-friendly, thermally resistance concrete with superior mechanical properties using an optimal ratio of FA and SF as a cement substitute. Given that HSC is more susceptible to spalling at temperatures exceeding 600℃, it is advisable to use RW in a proportionate amount. A small amount of RW can reduce environmental accumulation and reduce the effect of high temperatures on SF-containing concrete specimens. Splitting tensile strength, ultrasonic pulse velocity, and weight loss tests were performed on the produced concrete to determine its mechanical and physical qualities. Concrete color changes following heat exposure were also recorded.

2. MATERIALS

Portland cement manufactured by Tasik Company, which complies with ASTM C 150 [45] and Malaysian Standard MS 197-1-CEM I, was employed in this study. The coarse aggregate utilized was Kuari Nilai, with a diameter of 19 mm, and the natural siliceous sand had a maximum diameter of 4.75 mm. The specimens were mixed and cured using pure laboratory water devoid of salts and contaminants. To obtain RW, waste rubber tires were cut into 5×3×2 mm granules as shown in Figure 1 by a machine specifically designed for this purpose, it was added as a substitute material at a rate of 0.5% of the fine aggregate to limit its environmental impact and prevent samples from spalling at high temperatures.

Figure 1. RW granules shredded from tire

FA Class (F) replaced cement at 25, 30, and 35% weight replacement rates; SF remained constant at 10% of the cement weight in all mixes depends on the previous research recommendations, where they recommended that ratio is the optimal in performance. The sieve analysis of the aggregates used is displayed in Table 1. The chemical characteristics of cement and FA displayed in Table 2. Table 3 displays the properties of RW, whereas Table 4 displays the chemical properties of SF. The amount of SP plasticizer applied did not surpass 3% of the cement's weight, Table 5 displays the details and characteristics of SP material.

Table 1. Sieve analysis of the coarse and fine aggregates

Coarse Aggregate			
Sieve Size (mm)	**Mass Retained (gm)**	**Percentage Retained (%)**	**Percentage Passing (%)**
25	0.00	0.00	100
19	250	5.0	95.0
14	1100	22.0	73.0
12.5	1220	24.5	48.5
9.5	1455	29.1	19.4
6.3	635	12.7	6.7
4.75	315	6.3	0.40
Pan	25	0.40	0.00
Total	5000		
Fine Aggregate			
4.75	0	0	100
2.36	955	31.8	68.2
1.18	1029	34.3	33.9
0.60	577	19.2	14.7
0.30	335	11.1	3.5
Pan	104	3.5	0.00
Total	3000		

Table 2. Chemical characteristics of cement and FA used

Chemical Composition of Tasek Cement			
Items	**Clinker (%)***	**Cement (%)***	**ASTM C150 (%)**
SiO_2	21.66	21.28	20.6
Al_2O_3	5.8	5.6	4.4-6.0
Fe_2O_3	3.68	3.36	3.3-6.0
CaO	65.19	64.64	62.9
MgO	2.86	2.06	2.2-6.0
SO_3	0.2	2.14	2.1-3.0
Total alkalis	0.07	0.05	-
Insoluble residue	0.1	0.22	0.27-0.75
Loss on ignition	0.27	0.64	2.7-3.0
Chemical Composition of FA Class F Used			
Items	**Fly ash**	**ASTM C 618 (%)**	
Sio_2	45.24	Sum of $Fe_2O_3 + SiO_2 + Al_2O_3 \geq 70\%$	
Al_2O_3	23.15		
Fe_2O_3	12.71		
CaO	5.5	-	
MgO	2.5	-	
TiO_2	4.23	-	
K_2O	1.5	-	
SO_3	0.38	5 (max)	
Total alkalis	-	-	
Insoluble residue	-	-	
Loss on ignition	5.0	6.0 (max)	

Table 3. Properties of rubber waste (RW)

Properties	Result
Bulk density	1127 kg/m^3
Granules RW density	875 kg/m^3
Water absorption (24 hr)*	0.1
Specific gravity	1.52 gm/cm^3
Shape and size	Deformed granules (3-5) mm
Color	Black
Melting point*	175-200℃

*Details provided by manufactured company.

Table 4. Chemical compositions of silica fume (SF)

Composition	%
SiO_2	96.11
Fe_2O_3	0.64
Al_2O_3	1.10
MgO	0.61
CaO	0.30
SiC	0.29
Na_2O	0.63
K_2O	0.14
C	0.18

Table 5. Superplasticizer (SP) properties*

Product Name	Sikament® NN
Test standard	Complies with EN 934-2
Form and color	Liquid- Dark brown
Chemical base	Naphthalene formaldehyde sulphonate
Density	1.2 + 0.02 kg/liter.
pH (23 + 2℃)	8 + 1
Recommended dosage	0.5 - 3.0% by weight of cement

*Information provided from manufacturing company.

3. METHODS

This study encompasses a total of eleven various mixtures as indicated in Table 6, which consist of varying proportions of FA in relation to the weight of cement. The combinations range from 25% to 35% FA content, SF constitutes a constant proportion of 10% of the weight of cement, whereas RW accounts for 0.5% of the weight of fine aggregate. The rest percentages involved in production of one cubic meter of concrete are as follows: 22% cement, 27% fine aggregates, and 43% coarse aggregates. ACI committee 211.1 [46] used for mix proportion selection.

The w/c remains consistent at 0.35 for all mixes. Cylindrical molds measuring 100 mm × 200 mm were utilized for the inspection procedures. After subjecting the specimens to water treatment for a duration of 28 days, they were divided into three groups. The first group was tested at room temperature, while the second and third groups were heated in an electric oven. The oven’s temperature gradient system increases at rate of 9℃/min until reaching two different temperatures of 400℃ and 800℃, respectively. The specimen was subjected to an electric oven for a duration of two hours. Subsequently, the specimens were removed and allowed to cool on the table, exposed to ambient weather conditions before test. Multiple destructive tests were carried out. The splitting tensile strength (STS) test was conducted in accordance with ASTM C 496/C-17 [47]. Where the specimens were prepared for examination by placing it under the same device used to measure compressive strength (in another case study), surrounded at the top and bottom by an iron rod like a rib with a dimeter of 1 cm, and applying a load to the longitudinal axis until failure o ccurred. A high-precision ultrasonic non-destructive digital equipment, with an accuracy of 0.1 µs, was utilized to measure the ultrasonic pulse velocity (UPV) of the specimens as shown in Figure 2, where the upper and lower (circular) parts of the cylindrical sample, which represent the contact area between the concrete and the device’s sensors, were tanned with the gel intended for this test to increase the reading efficiency. A transducer operating at a vibration frequency of 55 kHz was utilized. The sound passage times (t, µs) of the concrete specimens were measured using the transmission technique [48]. According to the standard recommendations conducted by Jones and Facaoaru [49], the UPV test results were compared to the guideline values provided in Table 7.

Table 6. Mixes design proportions

Mix Code	W/C	Cement kg/m³	Water kg/m³	F.Agg kg/m³	C.Agg kg/m³	SF kg/m³	FA kg/m³	RW kg/m³	SP kg/m³
Cl	0.35	551	193	683	1081	0	0	0	12.5
ClRW0.5	0.35	551	193	679.6	1081	0	0	3.42	12.5
FA25	0.35	413	193	683	1081	0	138	0	12.7
FA30	0.35	386	193	683	1081	0	165	0	12.7
FA35	0.35	386	193	683	1081	0	193	0	13.1
SF10FA25	0.35	358	193	683	1081	55.1	138	0	13.0
SF10FA30	0.35	358	193	683	1081	55.1	165	0	13.2
SF10FA35	0.35	358	193	683	1081	55.1	193	0	13.4
SF10FA25RW0.5	0.35	358	193	679.6	1081	55.1	138	3.42	13.0
SF10FA30RW0.5	0.35	331	193	679.6	1081	55.1	165	3.42	13.6
SF10FA35RW0.5	0.35	303	193	679.6	1081	55.1	193	3.42	13.8

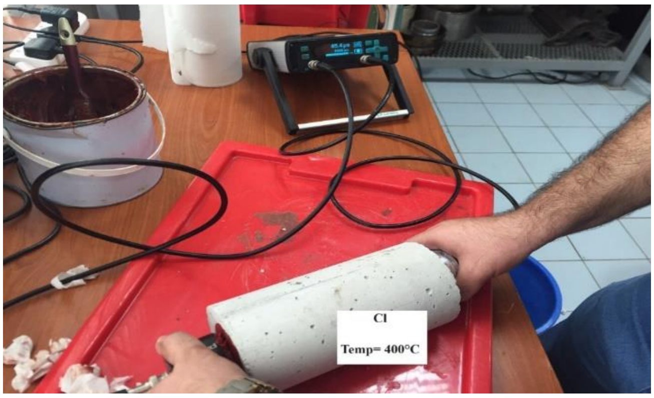

Figure 2. STS for specimens exposed to different temperatures

Table 7. Quality of concrete based on the ultrasonic pulse velocity test [47]

Concrete Quality	Longitudinal Pulse Velocity (km/sec)
Excellent	≥ 4.5
Good	3.5 - 4.5
Doubtful	3.0 - 3.5
Poor	2.0 - 3.0
Very poor	≤ 2.14

Eq. (1) determined how heating affected specimen weight. The specimens were weighed at normal and high temperatures using an electronic digital balance. Differences between readings were observed according to the equation:

$$W_{loss}\ \% = \frac{W_n - W_h}{W_n} \quad (1)$$

where, W_n= Specimen weight at normal temperature, and W_h= Specimen weight after heated.

4. RESULTS

4.1 Splitting tensile strength (STS)

The results revealed that adding RW at a low proportion (0.5%) increased STS strength by 7% at normal temperatures. Figure 3 shows the test results of different mixes and the standard deviation (s) value for every three samples. The improvement that occurred could be attributed to the fact that the inclusion of low amount of RW did not take up much space in place of the fine aggregate, thereby preserving the mechanical functional properties of each component of the mixture, which contributed to giving the concrete more ductility, resulting in fracture resistance. Also, the size of the

RW crumbs is close to that of fine aggregate, so replacing the fine aggregate with rubber crumbs didn't cause the void that could become a weak point to reduce the sample strength. The findings are consistent with previous research [3, 24]. Adding FA resulted in a steady loss of strength of up to 50% (FA35). The low pozzolanic reactivity of FA is a significant factor contributing to the reduction in strength and the prevalent dilution effect, particularly during the initial ages of specimen curing. Additionally, only a tiny proportion of FA has undergone a reaction [6, 44]. Because the FA took up a lot of space instead of cement in samples with high percentage of FA, the concrete lost a significant portion of the adhesion and cohesion properties it had gained from the presence of cement [3, 5].

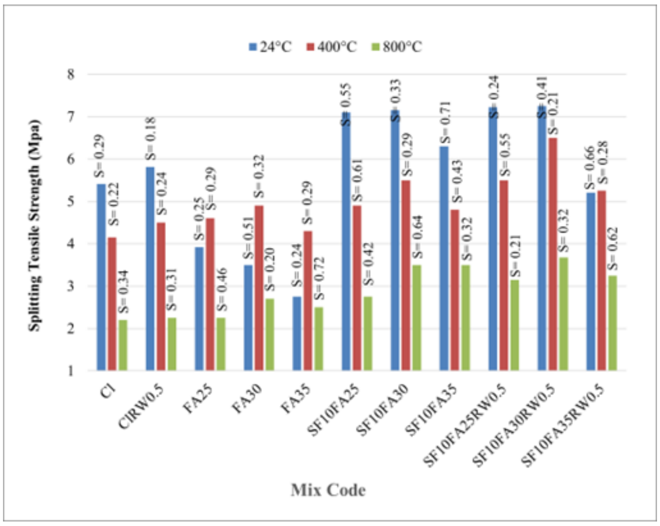

Figure 3. Results of STS specimens exposed to various temperatures

The inclusion of SF resulted in a significant increase in strength, reaching 32% (SF10FA30). SF particles contributed significantly to the endurance of interfacial transition zone (ITZ) between the aggregates and FA particles by filling voids with micro diameters or smaller (filler material) [2, 44, 50]. Their enhanced pozzolanic efficiency, on the other hand, increased cohesiveness strength. In collaboration with FA and cement particles, SF particles also efficiently contributed to redistributing the shape and size of concrete voids, the effects of which looked to strength enhancement.

Subjecting specimens to heat resulted in favorable as well as adverse results. The reference specimens (Cl) exhibited a 23% reduction in STS value when subjected to temperatures 400℃ compared to the same specimen tested at room temperature. The high temperature led to the decomposition of the bonding material's fundamental structure between the concrete components, causing the specimens to lose weight and convert into concrete that is weak in the face of fire resistance. The natural aggregate-cement paste bond began weakened as the temperature increased up to 400℃. The paste contracted as water was eliminated though the aggregates expanded [19, 51]. In addition, the breakdown of CH into CaO and its interaction with ambient moisture during cooling caused tiny cracks due to volume expansion.

In contrast, the RW container specimens had a diminished impact. The melting of RW granules in high-temperature concrete at 170℃-200℃ helped to reduce the incidence of cracks or spalls. Narrow channels were formed because of the melting process. They led to the reduction of internal pressure/stress in concrete specimens exposed to heat, resulting in the release of pressure-causing gases into the atmosphere [5, 17]. At 400℃, each specimen containing FA improved by as much as 18% (FA30) in comparison to the reference specimens exposed to the same temperature. The tobermorite product, resulting from the process of hydrated cement paste, exhibited the ability to retain water even at high temperatures.

This was attributed to the consumption of calcium hydroxide ($Ca(OH)_2$) and the positive impact of FA, which led to the reaction and information of pozzolanic C-S-H gels. These factors collectively contribution to reducing the stress caused by rapid recrystallization in specimens subjected to a temperature of 400℃ [2, 3]. A portion of the FA grains served as a filler material, effectively occupying the tiny voids, and resulting in a more compact concrete, hence enhancing the strength of the specimen. The RW facilitated the enhancement by offering escape paths that allowed the evaporation pressure to dissipate from the concrete specimens at an early stage, so averting the formation of significant cracks on the exterior of the sample body. This phenomenon also impeded the occurrence of spalling [2, 5, 50].

The specimens that combined SF and FA performed best at a temperature of 400℃. The maximum improvement in STS was 56.6% (SF10FA30RW0.5). The tobermorite phase ($5CaO.6\text{-}SiO_2.xH_2O$) was found to be an additional hydration product in both the FA concrete specimens and the FA concrete specimens including SF when the specimens were heated to 400℃, as validated by the XRD test conducted by Rashad [44]. This finding lends credence to the idea that the semi-crystalline phases can be transformed into tobermorite, a hydration product of exceptional efficacy. Reports indicate that tobermorite is three times more effective than C-S-H gel. This would clarify why the FA and SF specimens strength at 400℃ was greater than the control specimens strength at ambient temperature for all FA and SF specimens. Pozzolanic activity boosted C-S-H gel formation at 200℃-400℃. By adding SiO_2 from SF, the microstructure became more compact, enhancing the pozzolanic interaction with calcium hydroxide. The C-S-H gel strengthened the specimen and filled the pores, reducing permeability and improving concrete durability.

The principal cause of the reduction in strength for all specimens was raising the temperature to 800℃. The STS had a 61% drop (Cl), whereas the decrease in specimens containing FA was 50% (FA30). The residual strength of the specimens comprising SF and FA with RW was the best (SF10FA30RW0.5) which reached 67% at 800℃. The observed result can be ascribed to the pozzolanic reactivity derived from the use of SF and FA components. Moreover, the activation of the process was intensified by raising the temperature to 400℃. Additionally, the presence of RW waste facilitated the improvement by offering other escape channels. These channels allowed for the efficient removal of the generated vapour pressure from the concrete specimen at an early stage. Furthermore, the specimen successfully prevented the formation of cracks on its surface, and there was no occurrence of spalling within the temperature range of 400℃ to 800℃. Conversely, the reduction in strength may returned to exposing concrete to 600℃ causes Portlandite disintegration at 450℃ and the creation of Belite compound (C_2S), which increases concrete strength. However, a higher percentage of C_2S leads to slow hardening. Post-fire curing above 400℃ led to the formation of Portlandite with a reduced C_2S peak. With a gradual increase in temperature, Larnite (a C_2S polymorph), and calcium phosphate silicate were generated through C-S-H breakdown and transformation [18].

4.2 Ultrasonic pulse velocity (UPV)

The findings of the ultrasonic pulse velocity (UPV) test indicate the potential for accurately forecasting concrete quality based on this study. The findings indicated that the inclusion of 0.5% RW in the specimens (ClRW0.5) resulted in a minimal decrease in the concrete quality, but it remained within the acceptable range (good) as per the concrete quality classification specified in Jones and Facaoaru recommendations [49]. Figure 4 shown the test and standard deviation (s) results. The good performance remained when the cement was substituted with 25% and 30% of FA (FA25 and FA30), but its quality declined significantly when the FA content was raised to 35% (FA35), reaching a doubtful level. The addition of 10% SF to the mixtures comprising FA (SF10FA25-SF10FA35) or FA mixed with RW (SF10FA25RW0.5- SF10FA35RW0.5) resulted in improved quality of the specimens of concrete. The stabilization of the concrete's quality within the acceptable range was seen at normal temperatures. The enhancement is attributed to the presence of FA and SF particles, which have a finer diameter than cement. These granules work as fillers, effectively filling the holes and thereby increasing the density of the produced concrete.

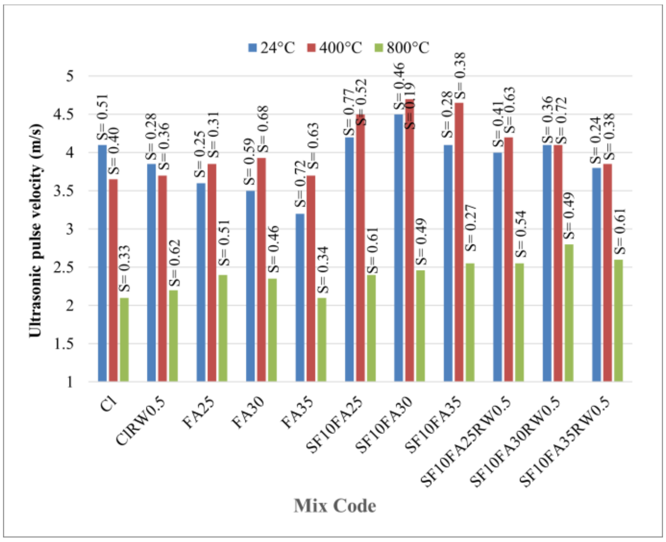

Figure 4. Results of UPV specimens exposed to various temperatures

The temperature of 400℃ had a notable impact on enhancing the quality of concrete, particularly in specimens consisting only of FA (FA30). The rate of improvement reached 7.6% compared to reference specimens subjected to the same temperature. The UPV values of the concrete showed an average increase when SF or a combination of SF and FA were present. This improvement amounted to 28.8% in the case of SF10FA30. Multiple studies have verified that, whether composed only of FA or a combination of FA with SF or FA with NS, is experiencing enhancement through the utilization of additive materials as fillers. This process effectively reduces the volume of voids or alters their size from large to medium to very fine [3, 5, 18, 52]. The pozzolanic reaction of both SF and FA after 28 days improved the ITZ, resulting in enhanced bonding between the cement paste and gravel, as well as between the cement paste and rubber. Consequently, the concrete became denser [2, 6, 53]. The UPV measurements of all specimens subjected to 800℃ exhibited a decrease in comparison to the specimens examined under normal conditions. Nevertheless, the measurements obtained from specimens containing a combination of SF, FA, and RW (SF10FA30RW0.5) showed a 33% improvement in comparison to the control specimen exposed to the identical temperature. The importance of SF and FA in preserving internal cohesiveness between the components was evident in the mechanical tests.

4.3 Effect of high temperatures on specimen surface

Concrete specimens exposed to temperatures of 400℃ and 800℃ underwent significant alterations in both chemical composition and physical appearance on the surface. These changes provide valuable indications that contribute to and validate the behavior of the materials employed. The temperature variation caused the concrete to transition from a light grey as shown in Figure 5a to a light brown (Figure 5b), and then to a faded grey color (Figure 5c). Visual observations confirmed that at a temperature of 400℃, the melted rubber began to appear on the outer surface of the specimens (Figure 5d).

Figure 5. Effect of various temperatures on specimens surface

These observations supported the interpretation that the rubber's behavior was influenced by the creation of gas exit channels within the heated specimens, which helped prevent spalling when the temperature reached 800℃. The phenomenon of color variations in concrete is attributed to the alterations in its physical and chemical properties induced by heat. The material undergoes desiccation upon exposure to heat. The initial change in color is a result of the progressive vaporization of water from the cement paste and the elimination of water that is chemically linked to cement hydrates. By subjecting cement paste to temperatures ranging from 500 to 550℃, portlandite decomposes as $Ca(OH)_2$ →

CaO + H_2O↑, causing rapid loss of content.

Another significant element influencing the color of the concrete after heating is the mineralogical composition of the aggregate. heated aggregates like limonite ($FeO(OH) \cdot nH_2O$) that contain iron compounds, hematite (Fe_2O_3), jarosite, and goethite, show the most significant color change. Since 70% to 80% of concrete is made up of aggregates, their performance is impacted by high temperatures. The color of concrete aggregates is mostly determined by their mineral structure [54].

The concrete specimen turned brown after being heated to 300°C for 1 to 2 hours. The color transitioned from light grey to pure white after 2 hours. After 1 hour at 400°C, the specimens turned light brown, and after 2 hours, they turned light ash. The color transitioned from pale ash to pale yellow after 3 hours of heating. The color changed from pale yellow to light grey after 3 to 4 hours. These variations were induced by changes in exposure duration and temperature, which resulted in the physical qualities of the concrete components being lost [55]. By analyzing the color of concrete surfaces on fire-damaged structures, scientists can acquire useful insights into alterations in the concrete's strength [5].

4.4 Effect of high temperature on specimen weight

To comprehensively evaluate the influence of components and variations in temperature on the weight of concrete specimens, two mixtures using waste materials (FA30 and SF10FA30RW0.5) were selected alongside the control mix (Cl) for investigation. The weight of concrete specimens containing FA as a replacement for cement is reduced by roughly 7% (FA30 and SF10FA30RW0.5) compared to the reference, as illustrated in Figure 6. The weight of these specimens was influenced by both the temperature and the presence of alternate materials. At a temperature of 400°C, specimens without FA (Cl) experienced a weight reduction of 2%.

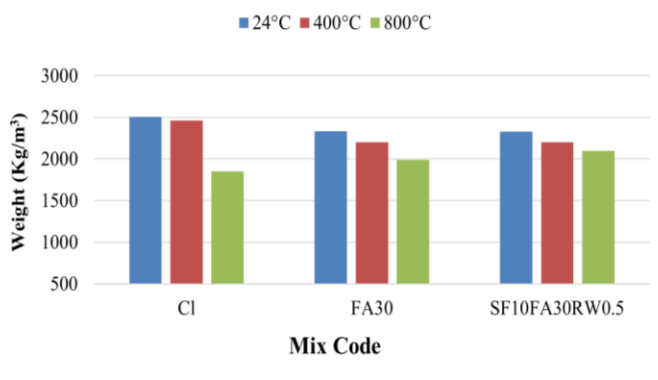

Figure 6. Effect of various temperatures on specimens weight

However, when the temperature was increased to 800°C, the weight reduction percentage for the same mix increased to 26%. At a temperature of 400°C, the weight of specimens containing FA (FA30) and (SF10FA30RW0.5) is reduced by 12% and 11.25%, respectively. The temperature of 800°C also exerts a greater impact on the same mixes, increasing their effects by 20% and 13%, respectively. It is observed that the specimens containing FA and SF exhibited a reduced impact rate at temperatures of 800°C in comparison to the reference specimen under the same conditions. This validates the precision of the outcomes from the destructive tests, which showed that the inclusion of FA and SF enhanced the residual strength of the concrete.

FA has a mass density that is around half that of cement. This makes it a significant factor in decreasing weight. Additionally, the presence of rubber, while in a small percentage, can cause tiny voids that are filled with FA particles instead of cement. The weight loss happened at a temperature exceeding 200°C, as determined by analyzing the chemical compositions of the waste materials in the specimen [11]. The process of decarbonization may continue beyond 600°C as a result of the combustion of any remaining organic material, particularly unburned carbon [56]. The weight loss seen in the specimens containing waste ash like rice husk ash treated at 700°C can be attributed to a reduction in the hydroxyl alcohol molecules, resulting in reduced water absorption into the silica molecules [12]. Moisture transfer from the concrete surface to the environment causes weight loss. This transfer changes the concrete's stiffness and mechanical properties, causing weight loss [3]. Due to changes in the physical and mechanical properties of concrete mix components, high temperatures cause weight loss. Concrete can lose 5% and 45% of its weight at 200°C and 1,200°C, respectively, for a certain time [57].

5. CONCLUSIONS

This study used local wastes such as FA and RW with Portland cement and SF to produce eco-friendly high-strength concrete. Concrete is denser when pozzolanic materials and industrial byproducts are used. However, the performance of concrete specimens containing different FA amounts and fixed SF and RW were heated to 400°C and 800°C is discussed. Results from this study suggest the following conclusions:

1. At normal temperature: For the STS specimens. the inclusion of 0.5% RW (ClRW0.5) enhanced STS by 7%, while replacing the cement by 25%, 30%, and 35% FA reduced the STS by up to31%, 37%, and 50%, respectively. By contrast, combining 10% SF with 30% FA enhanced the STS by 32%. For the UPV specimens, inclusion of 0.5% RW slightly reduced the UPV at normal temperatures, but the concrete quality remined within the acceptable range (good). When the cement was replaced with 25% and 30% FA (FA25 and FA30), the UPV specimens exhibited satisfactory performance, with slight reduction in quality reaching 16%. However, when the replacement was increased to 35% FA(FA35), UPV specimens performance became doubtful and the reduction in quality reached 30%. The UPV for mixes (SF10FA25-SF10FA35 or SF10FA25RW0.5-SF10FA35RW0.5) significantly enhanced the quality at the normal temperature, where the UPV improved to 28.8% (SF10FA30).
2. At high temperature: For the STS specimens, the specimens heated at 400°C decreased by 23% (Cl). While FA-containing specimens improved by 18% (FA30). The rate of improvement reached 56.6% (SF10FA30RW0.5) at the same temperature and in the presence of SF. At 800°C, the STS was reduced by 61% (Cl), whereas the specimens containing FA were reduced by 50% (FA30). The specimens combining SF, FA, and RW (SF10FA30RW0.5) showed the best reduction (33%) when compared to other combinations exposed to the same temperature degree. For the UPV specimens, the specimens containing 30% FA (FA30) exhibited quality improvement reached 7.6%

compared to the control specimens heated at 400℃. The UPV readings of all specimens heated to 800℃ were lower than those evaluated under normal conditions. However, specimens containing SF, FA, and RW (SF10FA30RW0.5) performed 33% better than the control specimen at the same temperature.
3. Concrete specimens exposed to temperatures of 400℃ and 800℃ underwent significant alterations in both chemical composition and physical appearance on the specimens surface. The temperature variation caused the concrete to transition from a light grey to a light brown, and then to a faded grey colour. Visual observations confirmed that at a temperature of 400℃, the melted rubber began to appear on the outer surface of the specimens.
4. Concrete specimens with FA instead of cement (FA30) and (SF10FA30RW0.5) weigh 7% less than the reference. Temperature and other components affected these specimens' weight. Specimens without FA (Cl) lost 2% weight at 400℃. When heated to 800℃, the identical combination lost 26% of its weight. FA Specimens (FA30) and (SF10FA30RW0.5) lost 12% and 11.25% weight, respectively at 400℃. The same specimens are affected by 20% and 13% more at 800℃. At 800℃, FA and SF-containing specimens had a lower impact rate than the reference specimen exposed to same temperature.

This study showcased the feasibility of utilizing and disposing of rubber waste (RW) in an urban context by adding it in tiny amounts into concrete. The study also validated the feasibility of substituting 30% of cement with fly ash (FA) in the production of one cubic meter of eco-friendly concrete. This type of concrete may be used for producing non-statically loaded construction parts such as surrounding blocks, pedestrian interlocking stones, and street sidewalk curb stones.

This study paves the way for future studies aimed at developing environmentally friendly concrete by exploiting similar or larger amounts of solid waste such as polypropylene (PP), polyethylene (PE), and others. Also, can use different pozzolanic materials in different amounts suitable for producing modified concrete with high strength and longer durability, such as nano silica (NS), nano clay, and others.

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NOMENCLATURE

℃	Temperature degree
s	Second
t	Time
Vs	Velocities
v	Ultrasonic pulse velocity, km/sec
W_h	Specimen weight after heating, kg
W_n	Specimen weight at normal temperature, kg

Greek symbols

μ	Poisson's ratio
μs	Microseconds
ρ	Concrete density, kg/m^3

Subscripts

FA	Fly ash
SF	Silica fume
RW	Rubber waste
Cl	Control
MS	Malaysia standard
STS	Splitting tensile strength
UPV	Ultrasonic Pulse Velocity
ITZ	Interfacial transition zone
F.Agg	Fine aggregate
C.Agg	Coarse aggregate