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A study of some relevant properties of concrete incorporating waste ceramic powder as a cement replacement agent

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ABSTRACT

Cement, the key ingredient in concrete, is responsible for 8% of the world's CO2 emissions. Thus, reducing the amount of cement used in concrete is highly desirable to lower the total embodied carbon in concrete manufacturing. Furthermore, an increasing amount of ceramic waste powder (CWP) is generated during the ceramics manufacturing process, which can result in severe environmental problems such as soil, air, and groundwater pollution. This paper reports the use of CWP as a cement replacement agent in concrete to reduce environmental pollution in both concrete production and CWP waste management fields. For this purpose, comprehensive laboratory work was carried out to replace different levels of cement with CWP. It was found that changes in compressive strength and water absorption value are within the acceptable tolerance when 20% CWP replaces cement. In addition, there was an improvement in thermal conductivity, and no significant damage to the mechanical properties of concrete after 30 min of fire exposure when CWP replaced 20% of cement was observed. Therefore, using up to 20% of CWP to replace cement in concrete manufacturing is feasible without compromising the essential properties of the finished products. The microstructural studies of the test specimens further proved that the added CWP was evenly scattered in the concrete matrix.

1. Introduction

Concrete has been the main material used in building and infrastructure construction for centuries, and it is estimated that the yearly consumption of concrete approaches 30 billion tonnes worldwide. Cement is an essential concrete component, but cement production is responsible for 5% of global carbon dioxide (CO_2) emissions, primarily due to the heating of limestone and clay [1]. Liu et al. [2] estimated that there could be an additional 85–105 Ct of CO_2 emissions over the next 33 years through cement consumption in concrete manufacturing. Mohamad et al. [3] further indicated that cement production could lead to dust, water, and noise pollution. Therefore, improving the sustainability of concrete and replacing cement with other materials are essential. There are many studies on using recycled materials or industry by-products, such as fly ash, silica fume, limestone, glass, crushed brick powder, and waste tyre rubber [4–7]. Therefore, using these recycled materials can reduce the cost and improve the sustainability of concrete manufacturing with no significant impact on concrete strength and durability.

Among recycled materials, there is a new tendency to study the potential use of ceramic waste powder (CWP) as a partial replacement for cement in concrete production. CWP is generated during the cutting and polishing of ceramic products (e.g., ceramic

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tiles), and the global generation of such waste exceeds 22 billion tons in 2018 [8]. The waste is mainly disposed into landfills, but such disposal can cause environmental problems such as soil, air, and groundwater pollution [9]. CWP contains a large proportion of silicon dioxide, aluminium oxide, and magnesium oxide, which can degrade plant surfaces (usually leaves), soil microbes, and other tiny organisms and act as a toxic agent on gill-breathing animals [9,10]. Collecting CWP and using it in concrete manufacturing can prevent waste from going into landfills and reduce environmental hazards [11,12].

Using CWP as a concrete cement replacement can eliminate the environmental hazards for concrete production and CWP waste management [11]. However, three major limitations exist in current studies that use CWP as cement replacement in concrete. Firstly, the effect of CWP on concrete's compression strength is unclear. Kannan et al. [13] replaced 0–40% of cement with CWP in concrete. They found that replacing cement with CWP reduced 28-day compressive strength of concrete. The reductions were 2.7% and 17.3% when CWP replaced 10% and 40% cement. Patel et al. [14] found a 5.8% reduction in compressive strength by replacing cement with 10% CWP. The strength reductions have also been reported by Subaşı et al. [15], AlArab et al. [16], and Raval et al. [17]. They claimed that adding CWP affected the bonding between cement and aggregate and reduced strength. However, Gautam et al. [18] indicated that compressive strength increased when CWP replaced 10% cement, possibly due to the pozzolanic reaction. The compressive strength was reduced when CWP content was increased further. Parashar et al. [19] also found a 6.9% increase in compressive strength when CWP replaces 10% cement. Bhargav and Kansal [20] supported the above findings by Gautam et al. [18] and Parashar et al. [19].

Thus, there are conflicting results on the impact of CWP on concrete strength, especially at the CWP replacement level of 0–10% [21]. Further tests are needed to clarify the effects of CWP on the compressive strength of concrete. Additionally, the changes in the compressive strength of concrete at different CWP levels may also be affected by the concrete grade and mix design. There should also be a model to predict the changes in the compressive strength of concrete based on its CWP replacement level and grade. However, such a model is lacking.

Secondly, water absorption is an essential durability property of concrete. Most studies have focussed on the water absorption changes when CWP was used for concrete aggregate or cement replacement in mortars, such as studies by Kannan et al. [13], Li et al. [22], Mohit and Sharifi [23]. Their results cannot be used to predict the water absorption changes when CWP replaced cement in concrete due to the difference in mix design. Furthermore, some conflicting findings exist among the few studies focusing on concrete's water absorption when CWP replaces cement. Parashar et al. [19] indicated a decreased water absorption rate when CWP replaced cement due to the concrete's porosity reduction [13,19]. However, Chen et al. [24] indicated that the water absorption rate decreased when the CWP replacement rate reached 10% and increased when CWP content increased further. Hence, more studies are needed to quantify the changes in water absorption for concrete when CWP replaces cement at different levels.

Furthermore, only limited studies quantified the changes in the thermal conductivity and fire performance of concrete when CWP replaces cement at different levels. Thermal conductivity is becoming essential in assessing whether CWP concrete can be used as building materials, as it is related to the energy savings of buildings [25]. Based on studies of concrete containing other recycled pozzolanic powders, such as glass, silica fume, and fly ash, there can be a potential reduction in the concrete's thermal conductivity due to the void-filling effect of these powders [26–28]. For example, Du et al. [26] found that adding 10% of glass powder to cement paste can decrease its thermal conductivity by 7.3%. Demirboğa [27] indicated that adding 10% silica fume and fly ash into cement reduced its thermal conductivity by 3.3% and 12.5%, respectively. However, no studies quantified the changes in thermal conductivity when concrete was mixed with CWP.

Additionally, the behaviour of concrete elements mixed with CWP when exposed to fires needs to be investigated in detail. Kodur and McGrath [29] indicated that pozzolanic powders may affect the bonding between cement and concrete, generating more cracks on concrete during fire exposure and affecting its mechanical properties. However, Yu et al. [30] showed that the filling effect of pozzolanic powders can improve the concrete's integrity when exposed to a fire and reduce the fire-induced degradation of mechanical properties. Given these conflicting findings, it is prudent to estimate the changes in fire performance of concrete containing CWP to estimate if using CWP concrete as a construction material can increase the fire hazard of the building.

Finally, only a few studies were reported on the microstructural and elemental composition analyses to investigate whether CWP, cement, and aggregate in concrete can be well bonded. The existing studies mainly use Scanning Electron Microscopic (SEM) technique to compare the microstructures of CWP and cement, such as those by Kannan et al. [13] and Chen et al. [24], or study the morphologies and element composition of mortar with CWP instead of concrete, as reported by Mohit and Sharifi [23] and Li et al. [22]. Hence, further studies are highly desirable to investigate the morphologies and element compositions of concrete specimens containing CWP.

Therefore, this paper focuses on the changes in concrete's compressive strength and water absorption at different levels of CWP replacement of cement. The changes in the workability (slump) of concrete at different CWP replacement levels were also studied. Based on the results obtained, models were developed to predict the changes in concrete strength and workability based on its grade and the CWP content. The thermal conductivity of concrete was also estimated at different CWP replacement levels. In addition, the mass loss and hardness of concrete were measured after fire exposure to determine the fire-induced deterioration in its mechanical properties. In addition, microstructural studies and elemental composition analyses of concrete specimens with CWP were carried out to investigate whether CWP, cement, and aggregate exhibit good bonding behaviour in the finished products.

This paper can clarify the impact of CWP on the compressive strength and water absorption of concrete. This paper will also develop the models that predict the changes in compressive strength and water absorption of concrete based on its CWP replacement level and grade, which has not been developed in previous studies. The paper also studies concrete's thermal and fire behaviour when CWP replaces cement, which has not been studied before. The main outcome of the present work is expected to guide the waste management of CWP and the sustainable design of concrete using CWP for the concrete manufacturers and construction industry.

2. Experimental methods

This study used the CWP to replace cement in concrete at 0, 10%, and 20% replacement levels. There are conflicting results on the impact of CWP on concrete strength and water absorption when CWP replaces 10% concrete, as reported by Subaşı et al. [15], AlArab et al. [16], Raval et al. [17], Gautam et al. [18] and Parashar et al. [19]. Therefore, a 10% replacement level was selected for this study to solve these conflicting findings and clarify CWP's impact on concrete. A CWP replacement level of 20% was also chosen to investigate the changes in concrete behaviour when CWP content increased further. These three different CWP replacement levels can also help to develop models that predict the changes in compressive strength and water absorption of concrete [31], as mentioned in the introduction section.

The concrete used for the experiment was Grade M40. This grade is commonly used to construct slabs, beams, columns, and footing. The impact of CWP on concrete properties was then investigated using a combination of test and regression analysis, and the details are summarized in Fig. 1.

2.1. Materials

The CWP was obtained from the final cutting and polishing process of ceramic products from the ceramic tiles manufacturing company in Melbourne, Australia. More than 50% by volume of the CWP particles had a size ranging between 5 and 10 μm. Fig. 2 shows the particle size distribution of CWP. Fig. 3 shows the scanning electron microscope (SEM) image of CWP at 500 times magnification. The powder had a similar shape to cement particles. It is expected to be well-bonded with other concrete mix design materials. Gautam et al. [18] have similar findings. CWP mainly contains silicon dioxide (SiO_2) (70%) and aluminium oxide (Al_2O_3) (18.30%). There are also other oxides, such as potassium oxide (K_2O) (3.95%), sodium oxide (Na_2O) (2.76%), and ferric oxide (Fe_2O_3), with the detailed elemental composition shown in Table 1.

Type I Portland cement was used in the study. The coarse aggregate (CA) was the natural crushed stone that complies with AS2758.1 [32] with a density of 1002.57 kg/m^3, and fine aggregate (FA) was sand that had a fineness modulus of 1.0 and a density of 925.45 kg/m^3. It had compliance with AS2758.1 [32]. The water-cement ratio of the concrete was kept at 0.40. Potable tap water was utilized to mix all the concrete ingredients and curing applications. Superplasticizer was also added to concrete to increase its workability.

Additionally, CWP was used as the cement replacement with mass replacement of 0, 10%, and 20% of Portland cement, respectively. The mix design of concrete per batch (total weight of 32 kg for each batch) with different CWP contents is shown in Table 2. The preparation for concrete followed AS1012.2 [33].

2.2. Concrete slump test

The slump test commenced immediately following the completion of mixing the test specimen. The mould for the slump test has a height of 300 mm. The mould was cleaned, and fresh concrete was filled in approximately three equal layers. Each layer was tamped with 25 strokes of the rounded end of the rod. The excess concrete was removed after filling and tamping, and the surface was cleaned with a trowel. Afterwards, the mould was raised, and the slump value was measured based on the difference between the mould height and the specimens' height. The details of mould design and test procedures are summarized in AS1012.3.1 [34]. The photographs of the slump tests are shown in Fig. 4.

2.3. Concrete compression test

The compression test followed AS1012.9 [35]. The specimens were conditioned at a temperature equal to 23 ± 2^{o}C in lime-saturated water until they reached 28 days of curing. Tests were performed on concrete cylinders that were 100 mm in diameter

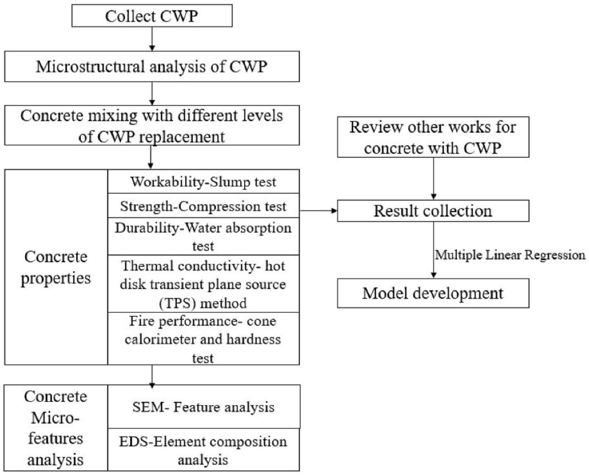


Fig. 1. A schematic representation of the methods to study CWP impact on concrete.

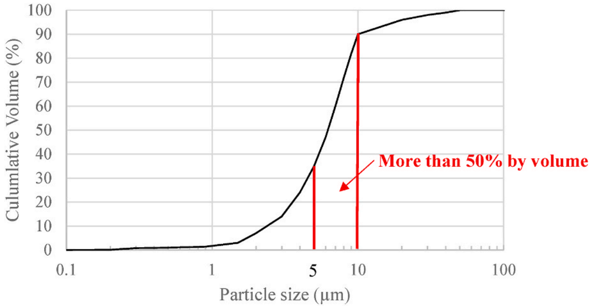


Fig. 2. Cumulative particle size distribution for CWP.

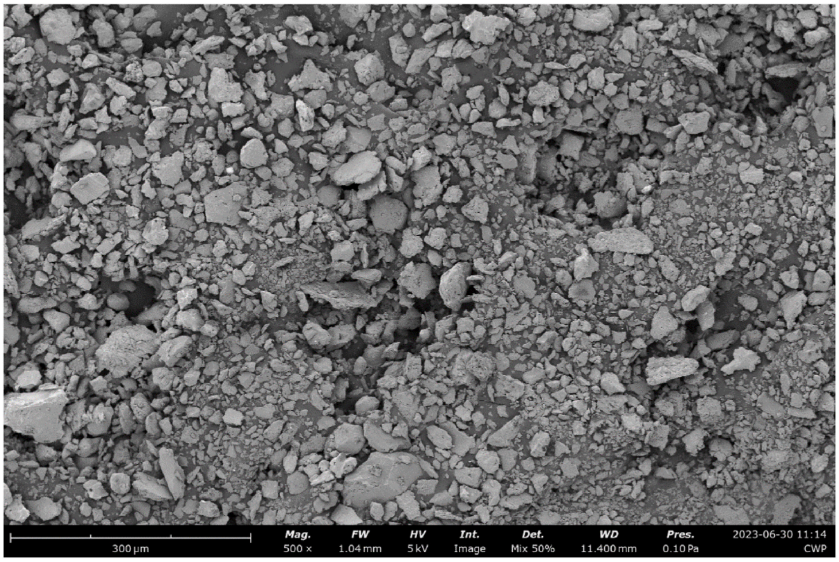


Fig. 3. SEM picture of CWP.

Table 1
Elemental composition of CWP based on the material datasheet provided by the manufacturer.

Chemical composition (Average)	Weight percentage (%)
SiO_2	70.00
Al_2O_3	18.30
K_2O	3.95
Na_2O	2.76
Fe_2O_3	1.40
MgO	0.69
TiO_2	0.66
CaO	0.58

Table 2
Concrete mix design (32 kg batches).

Material	Density (kg/m^3)	Mix 1 (Control), (g)	Mix 2 (10% CWP), (g)	Mix 3 (20% CWP), (g)
Cement	416.00	5324.00	4792.00	4259.00
CWP	0.0000	0.00000	532.000	1065.00
Fine Aggregate	925.50	11844.0	11844.0	11844.0
Coarse Aggregate	1002.6	12831.0	12831.0	12831.0
Water	–	2103.00	2103.00	2103.00
Super Plasticizer	–	27.0000	27.0000	27.0000

Fig. 4. Photographs of the slump tests.

and 200 mm in height. Compressive strength for each mixture was obtained from an average of four-cylinder specimens. The load was performed continuously at a rate of 140 kg/cm^2 per minute through a Universal Testing Machine (UTM) until failure and maximum load carried by the specimen were recorded.

2.4. Cold-water absorption

The water absorption test followed AS/NZS4456.14 [36] using cylindrical specimens 100 mm in diameter and 200 mm in height. The water absorption was obtained from an average of four specimens after 28 days of curing for each mixture. This test was carried out in two main steps: step one: the specimens were dried in the oven at 110 ± 8^{o}C until consecutive weights were reached. The weight of the specimens was recorded after they were cooled down at room temperature. In step two, the specimens were entirely immersed in cold potable water at an ambient temperature of 24 h. In this work, a 72-h immersion was also performed for each specimen to estimate its long-term water absorption behaviour.

The specimens were then weighted after immersion, and the cold water absorption was determined through the following equation:

$$w = 100(m_2 - m_1)\,/\,m_1 \tag{1}$$

where m_1 is the mass of dry specimens, and m_2 is the weight of the saturated specimen after cold water immersion.

2.5. Thermal conductivity test

The thermal properties of concrete at different CWP contents were investigated using a hot disk thermal constant analyzer through the Transient Plane Source (TPS) method. Concrete cylinders with 100 mm in diameter and 200 mm in height were cut into two samples of 10 mm in thickness. The surface of the cut samples was polished, and samples were dried in an oven at $105 \pm 5\,^{\circ}$C for 24 h before the tests. The hot disk sensor was sandwiched between two samples to act as a heat source and a temperature probe. The test setup is shown in Fig. 5, and the testing procedure follows ISO standards (22,007–2) to measure the thermal conductivity [37]. It is worth mentioning that, in this study, no heating was performed by the hot disk sensor to allow the concrete thermal conductivity to measure the room at room temperature (25^{o}C). In this way, the potential of concrete CWP to be used as a building envelope can be estimated.

Triplicate measurements were performed for the samples at each CWP replacement level to enhance accuracy, and the mean value was calculated. Apart from thermal conductivity, thermal diffusivity (mm^2/s) was also recorded to estimate the thermal performance of the concrete.

Fig. 5. Set up for the thermal conductivity tests.

2.6. Fire performance

Cone calorimeter tests offer a method for assessing and estimating the performance of concrete samples with different levels of CWP during/after fire exposure. The test configuration is shown in Pareek [38], and the setup used for the current study is shown in Fig. 6. The tested samples were 10 mm thick concrete plates cut from the cylinders. Before testing, samples were conditioned to constant mass at 23 ± 2 °C and relative humidity equal to 50%, following the requirements of ISO 5660.1 (2015) [39]. The testing procedure follows BS ISO 5660–1:2015 at 50 kW/m^2 radiant heat fluxes. The test can also be stopped after 30 min from starting if no signs of heat evolution are seen [39]. Mass loss of concrete during the cone calorimeter test was measured to investigate the water evaporation and internal damage of concrete.

The Schmidt rebound hammer test was performed before and after heating on the fire-exposure surface of the concrete to detect the changes in the mechanical properties (rebound hardness) of the concrete. The test was performed by an N-type Schmidt hammer following ASTM C805/C805M – 18, and impact points were randomly selected on the fire exposure surface [40]. The rebound hardness was determined by calculating the average value after ignoring 3 maximum values and 3 minimum values.

2.7. Microstructural studies for concrete

The Scanning Electron Microscope (SEM) and Energy Dispersive Spectrometry (EDS) analyses were carried out to evaluate concrete specimens' microstructures and chemical compositions. Based on the compression and cone calorimeter tests carried out in sections 2.4 and 2.6, it was found that concrete achieved the best mechanical strength when the CWP replaced 10% of the cement. Therefore, the SEM and EDS analyses were performed on the Mix 1 and 2 specimens, as shown in Table 1. The specimens with these mixed designs were broken into small pieces to conduct SEM and EDS tests. SEM test was performed using a Hitachi TM4000 II Benchtop equipped with the EDS system.

3. Results

3.1. Slump tests

The slump values of the specimens are shown in Fig. 7. The control mixture achieved a slump value of 105 mm. The slump value decreased by 33.3% and 52.4% when CWP replaced 10% and 20% of cement, respectively. It should be noted that the CWP particles have an irregular and angular shape. CWP also has a higher specific surface area than cement (1.5 times than cement, as reported by Kanaan1a and EL-Dieb [41]). Moreover, CWP can fill the spaces between cement particles. As a result, the friction between particles increases in concrete, and this increment can result in a decrease in slump value.

According to AS1379 [42], the tolerance of slump value should be ±30 mm if the slump is specified in construction (e.g., for carriageway and pavement construction). Thus, if concrete at a CWP replacement level of 10%–20% is used for carriageway and pavement construction, increasing the superplasticizer content and adding fly ash to the concrete is crucial. These two strategies can increase concrete slump value and workability by reducing internal friction among concrete particles.

A summary of the changes in slump value with CWP increment in different studies is shown in Fig. 8. The concrete grades for Patel et al. [14] and Bhargav and Kansal [20] are M25 and M20, respectively, with water-cement ratios of 0.46 and 0.50. It can be seen that the changes in slump values with CWP increment were lower, as reported by Patel et al. [14] and Bhargav and Kansal [20], than in this study. The high water-cement ratio of concrete in Patel et al. [14] and Bhargav and Kansal [20]'s study could be a possible reason, as water can contribute to the workability increment in concrete and offset the negative impact of CWP. Patel et al. [14] also detected an increase in the water-cement ratio when CWP replaced 10% cement. This may be because the aggregate used in Patel et al. [14] has less angularity and larger size, which can also offset the negative impact of CWP on workability.

Based on the regression analysis function in Excel, a multiple linear regression has been developed to predict the changes in slump value based on the grade of concrete and its water-cement ratio. The regression is shown in Equation (2):

$$\Delta S = 0.08M - 3.30\frac{W}{C} - 0.71CPW + 0.031M \times \frac{W}{C} \times CPW \tag{2}$$

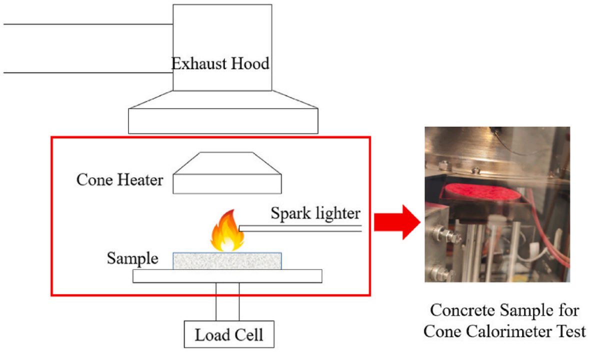


Fig. 6. Set up for the cone calorimetric tests [38].

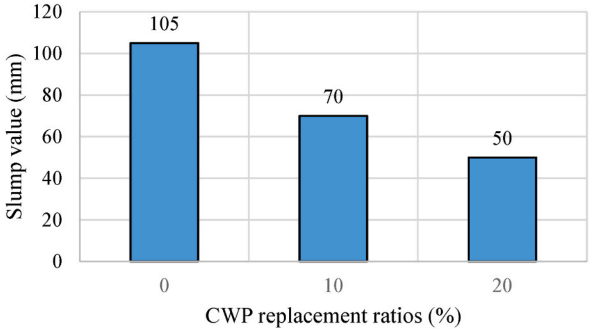


Fig. 7. Slump test values of concrete specimens at different CWP replacement ratios of cement.

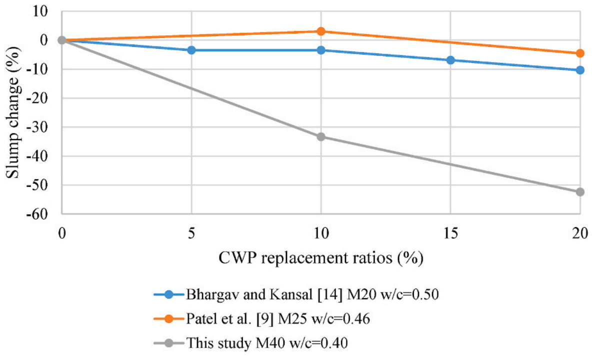


Fig. 8. Changes in the slump value for different concrete mix designs.

where ΔS is the changes in compressive strength of concrete (%, positive means strength increasing and negative means strength decreasing), M is the grade of concrete, $\frac{W}{C}$ is the water-cement ratio, and CPW is the level CWP replacing cement in concrete (%). The prediction achieves a high R Square value (0.68) and low standard error based on Table 3.

3.2. Compression test results

The compression test results for each concrete mix design are shown in Fig. 9. The compressive strength increased by 8.75% from 40.5 MPa to 43.5 MPa when CWP replaced 10% of the cement. The strength increment is due to the pozzolanic reaction, defined as the chemical reaction between reactive silica or alumina present in the CWP particles and portlandite formed during the cement hydration in the presence of water at ambient temperature [43]. The pozzolanic reaction can form additional cementitious compounds (C-S-H) and increase compressive strength. The reaction can also reduce the alkali content and prevent the alkali–silica reaction (ASR) in concrete [44]. Increasing the water in a concrete mixture can contribute to the pozzolanic reaction [45]. The level of reaction can also be increased by increasing the curing temperature and curing time of concrete [46]. These strategies can further improve the strength of concrete when CWP replaces cement (see Fig. 10).

Also, CWP contains ferric oxide and titanium dioxide (Fe_2O_3 and TiO_2, shown in Table 1). The existence of Fe_2O_3 can potentially increase the performance of cement-based material by compacting the cement [47]. TiO_2 can also accelerate the hydration of concrete at early ages due to its nucleation effect and improve its compressive strength [48].

Compressive strength was reduced by 10.3% when CWP replaced 20% of the cement. A further increase in CWP's content generally weakens bonds between cement and aggregates [49]. Additionally, when high-volume CWP was used, the amount of silica available in the concrete mix was too high, and the amount of calcium hydroxide produced from cement hydration was insufficient to react with the available silica [50]. Therefore, some silica was left without reaction [51]. CWP also contains alkali content ($Na_2O + K_2O$) that can

Table 3
Statistical analyses of data relating to the slump tests.

Regression Statistics	
Multiple R	0.85
R Square	0.72
Adjusted R Square	0.45
Standard Error	3.11
Observations	11.0

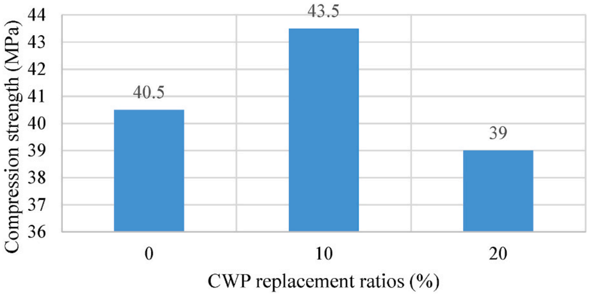


Fig. 9. Compressive strength of concrete specimens at different CWP replacement ratios of cement.

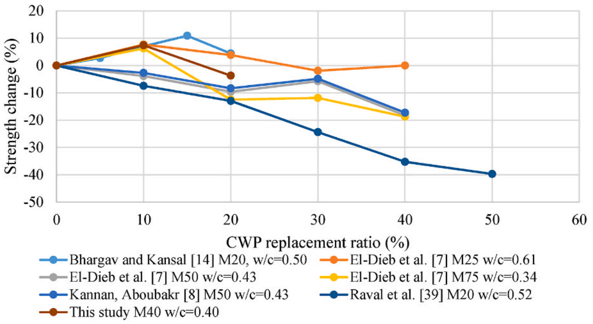


Fig. 10. Changes in compressive strength for different concrete mix designs.

lead to the Alkal-Silica Reaction (ASR) and results in the expansion and cracking of the concrete [52]. The composition of alkali content is low when CWP replaces 10% of cement. However, the alkali content increment can contribute to ASR when the replacement ratio increases.

Regression Statistics	
Multiple R	0.82
R Square	0.67
Adjusted R Square	0.60
Standard Error	3.84
Observations	34.0

3.3. Water absorption

The changes in water absorption for different concrete mixes are shown in Fig. 11. There was a slight increase in water absorption from 5.9 % to 6.4% for the 24-h immersion test when CWP replaced 10% and 20% of the cement. For the 72-h immersion test, the corresponding water absorption increased from 6.1% to 6.5%. As mentioned earlier, CWP has alkali content ($Na_2O + K_2O$) that can lead to the expansion and cracking of the concrete through ASR [49], which also increases its water absorption. However, CWP particles can also fill voids between concrete ingredients and densify concrete's microstructural. The Fe_2O_3 content in CWP can also

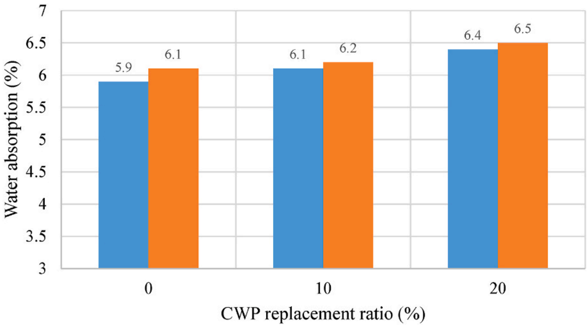


Fig. 11. Water absorption of concrete specimens at different CWP replacement ratios of cement.

compact the cement and densify the concrete microstructure [47]. There was a 5.45% increase in concrete density by replacing 20% of cement with CWP, based on the density measurement following AS 1012.12.1. These void filling and compacting effects can offset the water absorption increment caused by concrete porosity growth. Therefore, the water absorption increase is insignificant (up to 8.3% only) when CWP replaces 0–20% cement.

The pozzolanic reaction caused by CWP can also affect the water absorption of concrete. Meddah and Tagnit-Hamou [53] indicated that forming C–S–H can cause concrete microstructure densification, decreasing its porosity and water absorption. López and Castro [54] further show that hydration products from natural pozzolans can reduce concrete pore connectivity and water absorption. However, the reducing effect of the pozzolanic reaction on water absorption is not reflected in Fig. 11. This may be because 28 days of curing is insufficient for the pozzolanic reaction to change the concrete's porosity, and a longer curing time can be used for manufacturing concrete containing CWP.

3.4. Thermal conductivity analysis

Fig. 12 shows concrete's thermal conductivity and diffusivity at different CWP replacement ratios. It can be seen from Fig. 12 that replacing cement with CWP can increase concrete's thermal insulation by reducing its thermal conductivity and thermal diffusivity. Specifically, there was an 11.2 % reduction in thermal conductivity and a 13.6% reduction in thermal diffusivity when the replacing ratio increased from 0 to 20%. Adding CWP in concrete can increase its SiO_2 composition and reduce thermal conductivity. Besides, CWP particles can reduce the size of air voids within the concrete and turn large air voids into a couple of small ones [55]. There are shells of protected cement paste surrounding air voids in concrete. The increasing number of small air voids can increase the shells' thickness and improve the concrete's thermal insulation. The growing number of small voids may also increase the total surface area of air voids and prevent the transfer of heat in concrete, leading to an increase in the thermal resistance [26,27,56]. The result indicates that replacing cement with CWP can reduce heat loss from a building if such concrete is used as building fabric.

3.5. Fire performance analysis

Fig. 13 shows that, for concrete samples with or without CWP, no spalling or observable cracks occurred on their fire exposure surface after the cone calorimeter tests (test duration is 30 min). The formation of spalling and cracks during heating is usually caused by the uneven expansion of cement and aggregate in concrete. The test results indicate that adding CWP to concrete does not contribute to this uneven expansion.

The effect of fire exposure on the mass loss and mechanical properties of concrete containing different levels of CWP is shown in Figs. 14 and 15. There are some uncertainties in the first 15 min of fire exposure due to water evaporation. After 30 min, the mass loss for the concrete sample when CWP replaced 10% cement (4.01%) was 15.2% less than when no CWP replaced concrete (4.62%). When CWP replaced 20% cement, this mass loss for the concrete sample (5.33%) became 15.3% higher than when no CWP replaced concrete. Mass loss of concrete exposure to fire occurs due to the evaporation of free water and damage (e.g., spalling, internal cracks, internal voids, and segregation) to concrete samples [57,58]. Fig. 14 thus indicates that replacing 10% cement with CWP may reduce the interior damage in concrete samples after fire exposure.

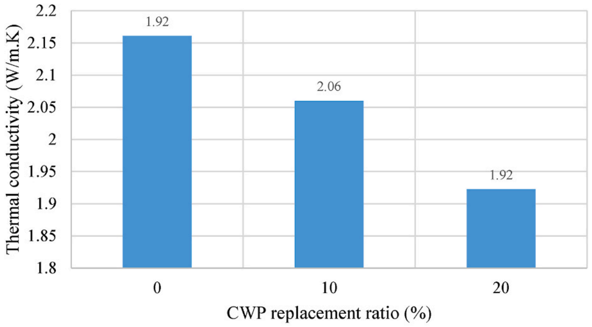
The rebound hardness measurement in Fig. 15 further illustrates that mechanical degradation for concrete when CWP replaced 10% cement was less than when CWP replaced 0 and 20% cement. As mentioned, CWP can densify concrete microstructure through pozzolanic reaction and improve its fire performance [55]. Furthermore, CPW particles can intermix with the cement grains and pack into the voids between the fine aggregate particles to prevent crack initiation and propagation. Replacing cement with 20% CWP can affect the bonding between cement and aggregate and degrade concrete performance during the fire. However, at this replacement ratio, L_t/L_o is only 6.2% less than the concrete sample without CWP. The changes in L_t/L_o are within the acceptable range [59].

3.6. Microstructural analysis

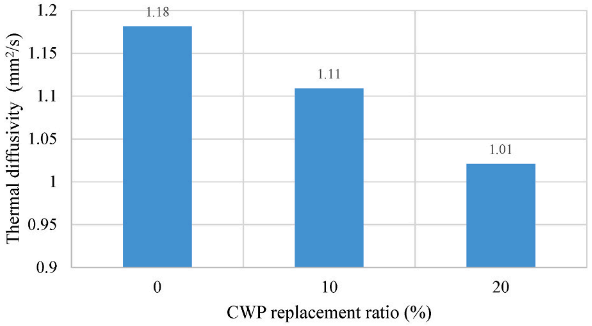
Fig. 16 shows the microstructure of the concrete specimens when CWP replaces 0 and 10% cement at 5000 times magnification. It can be that there are limited micro cracks formed in both cases, which indicates that the existence of CWP does not significantly affect the bonding between cement and aggregate. The white dots in Fig. 16(b) are the CWP particles, confirmed by the EDS analysis in Fig. 16(c). CWP particles are thoroughly encapsulated and dispersed into the cement, which can be well-bonded with aggregate in concrete due to its smaller size. The SEM images show no apparent cracks when CWP replaces 10% cement. This indicates that the ASR reaction in concrete is not significant at this replacement ratio. However, more microstructural studies are needed to detect the integration between CWP and cement, the changes in concrete porosity, and the level of pozzolanic and ASR reactions.

3.7. Flexure strength

In this study, the flexure strength was not tested. However, many studies have developed empirical equations to predict flexural strength based on compressive strength, as summarized in Table 4. Bhargav and Kansal [20] and Kumar and Reddy [60] have collected the compressive and flexure strength for concrete when CWP replaces different levels of cement. Their data was input into each equation in Table 4 to check which equations are reliable for concrete containing CWP. R^2 value of each equation is summarized. Table 4 shows that Esquinas et al. [61]' s equation can give a more accurate prediction of flexure strength for concrete containing CWP. The flexure strength for concrete in this paper can thus be predicted using Esquinas et al. [61] and compressive strength in Fig. 9. The prediction outcome is shown in Fig. 17.

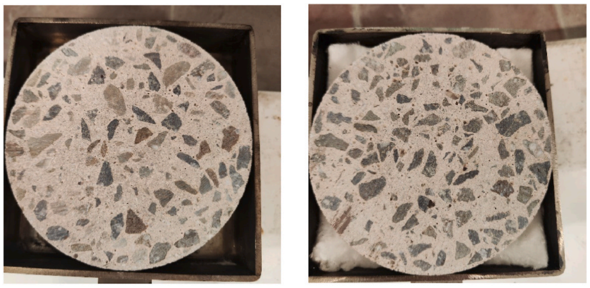


(a) Thermal conductivity



(b) Thermal diffusivity

Fig. 12. Thermal performance concrete samples at different CWP replacement ratios of cement.



(a) Before test (b) After test

Fig. 13. Fire exposure surface of concrete samples after cone calorimeter tests (Sample at CWP replacement ratio of 20% as representatives).

4. Discussion and future works

From the tests and analysis of results, the following discussion can be drawn:

1. The test results indicated that the changes in compressive strength are up to 10.3%, and the water absorption of concrete ranges from 5.9 % to 6.4% for the 24-h immersion test when CWP content increases from 0 to 20%. According to IS456 [59], the acceptable tolerance for compressive strength is ±15%, and the acceptable average water absorption value of the concrete is between 5.5% and 6.5% for typical commercial concrete. Both properties are within the acceptable range required by standards. Therefore, it is feasible for concrete with CWP up to 20% to be commercialized and widely used, especially for lightweight concrete partition wall construction and concrete bricks where the concrete workability requirement is not high. However, more studies are needed to investigate the critical properties of concrete containing CWP to fully understand its feasibility in the construction industry, including fire resistance, thermal insulation, acoustic insulation, etc.
2. Replacing cement with CWP can reduce the slump of concrete. Thus, increasing the slump and workability of concrete containing CWP is essential, especially if the slump is specified in construction. As mentioned earlier, adding fly ash and superplasticizer to

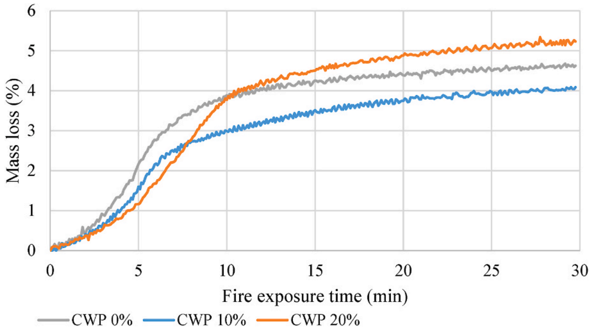


Fig. 14. Mass loss of concrete samples at different CWP replacement ratios of cement during cone calorimeter tests.

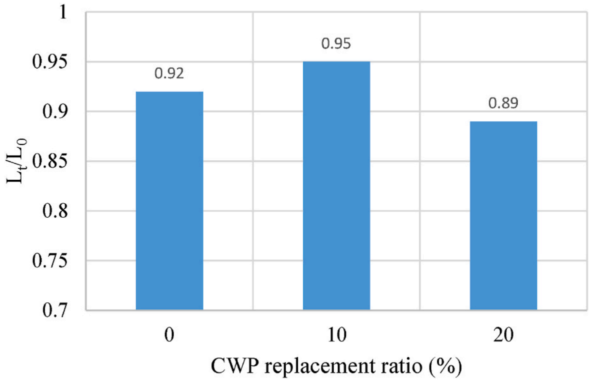


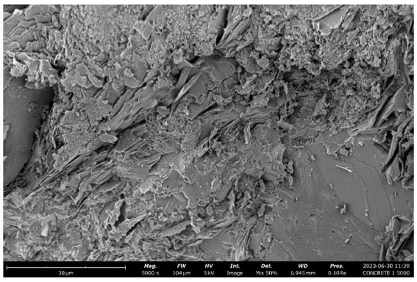
Fig. 15. Rebound hardness reduction (L_t/L_o) of concrete samples at different CWP replacement ratios of cement after cone calorimeter tests (Note: L_t and L_o are the rebound hardness before and after fire exposure).

concrete can increase its workability. Reducing the angularity and flakiness of aggregate and increasing the aggregate size are alternative solutions to increase concrete's workability [68]. Additionally, concrete workability can be improved by adding silica fume, copper slag, blast furnace slag powder, and palm oil fuel ash [69,70]. Further studies are needed to optimum the mix design for concrete containing CWP by considering all the solutions. The aim is to ensure that the workability of concrete can be improved without a significant effect on its strength and durability.

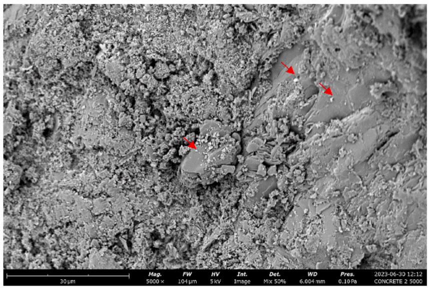
3. It is believed that the pozzolanic reaction is the primary reason for the increase in concrete's compressive strength. The pozzolanic reaction can lead to less reduction in mechanical properties for concrete when CWP replaces 10% cement after fire exposure than concrete without CWP. To further explore the pozzolanic reactions in concrete, X-ray diffraction and thermal infrared spectroscopy analysis should be carried out to investigate the formation of different cementitious compounds in concrete.
4. Concrete porosity is the primary factor affecting concrete's water absorption, durability and thermal conductivity [71,72]. It is worthwhile to quantify the concrete porosity at different levels of CWP content further to understand changes in concrete water absorption and permeability. The quantification of concrete porosity can also help to predict the changes in acoustic insulation and corrosion resistance of concrete containing CWP. The analysis can be performed using SEM and ImageJ software (an image processing program).
5. Further work needs to be carried out to understand concrete's thermal behaviour and fire performance. In this paper, the thermal conductivity of concrete is measured at room temperature. It is essential to measure the changes in thermal conductivity when CWP replaces different percentages of cement at elevated temperatures, as the internal cracks caused by elevated temperatures may affect the thermal conductivity of concrete. Also, further tests need to be carried out to study the fire performance of concrete at various fire exposure times and perform microstructural studies to estimate concrete damage after fire exposure.

5. Conclusion

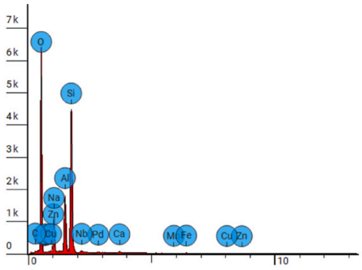
In summary, this paper investigated the potential of using CWP as a cement replacement in concrete. The changes in slump, compressive strength, and water absorption of concrete when different CWP levels replace cement were studied. It was found that the slump value decreased by 33.3% and 52.4% when CWP replaced 10% and 20% of the cement, respectively. It has also been found that the compressive strength increased by 8.75% when CWP replaced 10% CWP and decreased by 10.3% when CWP replaced 20% CWP. The concrete's water absorption increase is relatively nominal (up to 8.3% only) when CWP replaces 0–20% cement. The changes in compressive strength and water absorption value are within the acceptable tolerance. Also, there is an improvement in thermal conductivity and no significant damage to the mechanical properties of concrete after 30 min of fire exposure when CWP replaces 20%



(a) 5000 times magnification (Replaces ratio 0)



(b) 5000 times magnification (Replaces ratio 10%)



Element Symbol	Element Name	Weight Conc.
C	Carbon	1.399
O	Oxygen	47.353
Na	Sodium	8.192
Al	**Aluminium**	**12.787**
Si	**Silicon**	**26.573**
Ca	Calcium	0.699
Mn	Manganese	0.200
Fe	Iron	0.500
Cu	Copper	0.400
Nb	Niobium	1.199

(c) EDS analysis of CWP

Fig. 16. Microstructural analysis of concrete when CWP replaces 0 and 10% cement.

Table 4
Relationship between flexural and compressive strength and the accuracy of prediction for concrete with CWP.

Authors	Equation	R^2 in flexure strength prediction
Raphael [62]	$f_r = 0.438 f_c^{2/3}$ (MPa)	0.757
Xu and Shi [63]	$f_r = 0.39 f_c^{0.59}$ (MPa)	0.756
Amudhavalli et al. [64]	$f_r = 0.039 f_c^{1.35}$ (MPa)	0.763
Pul [65]	$f_r = 0.034 f_c^{1.286}$ (MPa)	0.763
Ramadoss [66]	$f_r = 0.259 f_c^{0.843}$ (MPa)	0.759
ACI318-14 [67]	$f_r = 0.62\sqrt{f_c}$ (MPa)	0.756
Esquinas et al. [61]	$f_r = 0.0763 f_c + 4.3751$ (MPa)	0.790

cement. Therefore, using up to 20% of CWP to replace cement in concrete manufacturing is feasible. The microstructural studies further proved such a feasibility by finding CWP evenly scattered in the concrete. The paper can benefit the CWP waste treatment and concrete manufacturing industry by reducing the amount of CWP waste and increasing the sustainability of concrete production.

CRediT authorship contribution statement

Le Li: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Conceptualization. **Paul Joseph:** Writing – review & editing, Supervision. **Xuelin Zhang:** Investigation. **Lihai Zhang:** Writing –

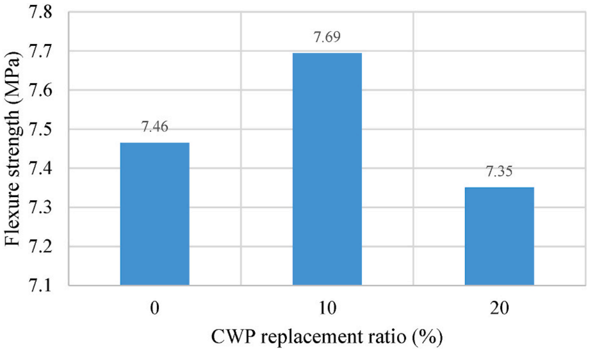


Fig. 17. Flexure strength of concrete specimens at different levels of CWP.

review & editing, Supervision, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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