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The Potential Use of Ground Ceramic Tile Waste as Partial Cement Replacement in Mortar

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Abstract

In line with sustainable development goals, waste generated from the construction industry that increases annually need to be well managed to ensure environmental sustainability. Ceramic waste is type of solid waste generated at construction site and disposed at landfill which contribute towards environmental pollution. The present research investigates the effect of ground ceramic tile as a partial cement replacement on properties of mortar. Six mixes consisting 0%, 10%, 20%, 30%, 40%, and 50% of ceramic tile powder by weight of cement were tested. The mixes were subjected to setting time test, flow table test, compressive strength and water absorption test. Inclusion of tile powder up to 50% increases the final setting time, but not more than 6.5 hours. Upon blending 10% and 20% tile powder, the flowability value of mortar mixture reduced slightly from 190mm to 185mm and 180mm respectively. The inclusion of 20% tile powder produces mortar with compressive strength of 39.50MPa due to the pozzolanic reaction of the powder. Success in integrating ceramic tile waste as cement replacement would reduce quantity of waste disposed and promotes a cleaner environment.

1. Introduction

Globally, the growing construction industries continue to use concrete as main construction material. The rising demand for concrete production has also boost the raw materials supplying industries such as cement, aggregate quarrying and sand mining sector. This has positively contributed towards income generation of the nation. At the same time, this industry also causes degradation of environment owing to its consumption of non-renewable resources as well as the processing stages in the factory. This industry is releasing about 7% of carbon dioxide emissions [1]. The process of limestone calcination emits large portion of CO_2 which is more than 50% from the total carbon dioxide emitted during cement production [2]. The presence of pollutants and fine particles has been shown to have detrimental effects on several environmental domains, including climate change, ozone depletion and acidity of water and soil. Thus, discovering alternative material that can be integrated as partial cement substitute without it being processed via thermal treatment that consume high energy and CO_2 emission would be one of the options. Scrivener et al. [3] highlighted that the approach of utilizing supplementary cementitious materials to substitute portion of Portland cement clinker is the most effective method to reducing emission of cement industry. In view of environmental sustainability, approach of using local waste as mixing ingredient for cement production would minimize natural resources reaped from the nature, lessen waste ending at landfill, reduce emission from cement trade and ensure well-being of the community.

Construction and demolition waste (CDW) is responsible of largest share to the total waste generated in modern society. The amount of CDW is increasing with the urbanization in many parts of the world [4]. A significant proportion of higher than 35% of CDW is thrown at dumping ground annually on a global scale [5]. The global volume of CDW is expected to exceed 10 billion tons per year [6]. Ceramic tile waste is one of the materials that is generated during construction project. The ceramic products include wall and floor tiles, sanitary ware and household ceramics [7]. The global production of ceramic tiles amounted to a staggering 12.6 billion square meters in 2019 [8]. At the same time, a substantial quantity of ceramic tile waste (CTW) is generated each year [9]. A significant proportion of CDW, above 45%, consists of ceramic waste from the construction industry [10]. It usually disposed of in landfills. Continuous disposal of this waste would lead to long term problem in terms of environmental pollution and health issues [10]. Since waste dumping at landfill and incineration pollutes the environment and release greenhouse gasses, approach of blending waste in concrete production would reduce building trade's carbon impact [11]. Alleviating waste from being disposed would lighten the burden of industry in managing waste, preserve land for better use and promote cleaner surroundings for the well-being of society.

The presence the considerable quantity of silica and Almunia would contribute to pozzolanic reaction and improves the overall performance of cement based composite. This oxide composition attracts the researcher to incorporate the ceramic tile powder as cement replacement in cement based composite. Many researchers found that the utilization of CTP as cement replacement up to certain limit has beneficial impact on the mechanical strength of cement-based composite [12-14]. However, alternative studies show a decline in mechanical strength concrete of cement-based composite [15-16]. Despite there have been research on the utilisation of ceramic tile powder (CTP) as a cement substitute in cement based composite mixture, the effects on strength and durability varied depending on the mixture and the quantity of CTP substitution. There were no regulations for employing CTP as a partial cement substitution in cement based composite mixtures. The CTP replacement level utilised to optimise cement based composite performance will be determined by personal expertise and experience with the material. As a result, providing a mechanism for selecting CTP replacement is critical, allowing practitioners to simply determine the CTP replacement level required for a given performance.

Thus, the aim of this study was to optimize (CTP) as mixing ingredient in mortar. The present research explores the potential use of locally generated ceramic tile waste as partial cement replacement for mortar production. The paper presents the characterization results of CTP in terms of its pozzolanicity and the setting time results of paste blended with CTP. Then, the performance of mortar upon incorporation of CTP on its flowability, compressive strength and water absorption is also reported in this paper. Furthermore, this study explores the optimum design mix of CTP as cement replacement by utilizing a central composite design (CCD) relied on RSM.

2. Methodology

The experimental work conducted comprised of three stages. The first stage consists of raw material preparation and basic properties testing task. Then, followed by preparation of samples required for testing. The final stage involves testing of the samples.

2.1 Materials

Cement, water, sand and ground ceramic tile powder illustrated in Fig. 1 is used to produce specimens in this research work. The research employed Ordinary Portland cement (OPC) of grade 52.5 N, which was produced in adherence with the provisions outlined in ASTM C 150-07 [17]. River sand was employed in this study. The mixing and curing process involved the utilize of tap water. Ground ceramic powder processed at the laboratory is used as partial cement substitution material. The discarded broken ceramic tiles supplied by local hardware shops were initially dried in an oven. The temperature used for drying is 110 °C for 24 hours. Then, it was crushed by means of mechanical apparatus, followed by screening through a 4.75 mm sieve to eliminate larger particles. To meet the ASTM 618-19 [18] requirements, mandating that 66% of the particles must have a size of 45 μm or less, the screened ceramic tile waste was further ground for a duration of 12 hours. The present investigation utilised a modified Los Angeles machine for grinding process. The resulting powder was deposited in a container. The specific surface area of the ground ceramic tile powder and OPC is 1380 m^2/kg and 913 m^2/kg respectively. Fig. 2 depicts the waste processing stage from big pieces of tiles which turned into smaller size via crushing process and finally ground to be powder form. Based on the data in Table 1, ceramic tile powder which consist more than 70% of total $SiO_2 + Al_2O_3 + Fe_2O_3$ can be categorized as Class F in accordance ASTM C618-19 [18].

Fig. 1 *Mixing ingredients used*

(a) (b) (c)

Fig. 2 *Broken ceramic tile transformed into smaller piece before ground to be powder form*

Table 1 *Chemical composition of ground ceramic tile*

Oxide	Ground ceramic tile %
Silicon dioxide (SiO_2)	57.1
Aluminium Oxide (Al_2O_3)	16.6
Ferrous Oxide (Fe_2O_3)	4.19
Magnesium Oxide (MgO)	1.10
Sulfur Trioxide (SO_3)	0.22
Alkalis (Na_2O)	1.24
Potassium Oxide (K_2O)	2.60

2.2 Sample Preparation

Six types of mixes were produced and tested in this research work. The compositions of these mixes are presented in Table 2. The set of mixtures consisted of a control sample (CTP0) and five additional samples (CTP10 to CTP50) incorporating 10%, 20%, 30%, 40%, and 50% CTP as a replacement for cement, respectively. The weight ratio of cement to sand in the mortar samples was maintained at a ratio of one part cement to 2.75 parts sand. To attain comprehensive homogenization of all constituents, an immaculate mortar mixer was employed. The procedure of blending sand, CTP, and cement was achieved within a time frame of three minutes. Water was added to the mortar and mixed to ensure proper homogeneity before filled in moulds. Then, the mixture in the moulds were compacted and then protected with wet gunny. After 24 hours, cubes were demoulded and submerged in water for curing. Fig. 3 depicts mortar cube preparation process.

Table 2 *Mix proportion (kg/m3)*

Mix	OPC	CTP	Sand	Water
CTP0	657	1810	1810	361.35
CTP10	591.3	65.7	1810	361.35
CTP20	525.6	131.4	1810	361.35
CTP30	459.9	197.1	1810	361.35
CTP40	394	262.8	1810	361.35
CTP50	328.5	328.5	1810	361.35

(a) **(b)** **(c)**

Fig. 3 *Mortar cubes preparation work*

2.3 Testing

The strength activity index test was done to evaluate the pozzolanic reactivity of the ceramic tile powder used in accordance to ASTM C311-22 [19]. Setting time test utilizing vicat apparatus was carried out in adherence with ASTM C191-08 [20]. Before the testing began, the materials required for paste preparation is measured. First, the cement and ceramic tile powder were mixed uniformly. Then, water was added and then mixed homogenously before shaped like a ball using hand. After that, the paste was filled in the conical ring and any leftover paste was removed. The conical ring was positioned on a base plate before the molded specimen was placed in the Vicat apparatus. Initial setting time and final setting time was determined. The effect of integrating CTP on consistency of mortar mixture were determined via flow table testing. The testing was conducted using a clean and dry manual flow table adhering to the testing method as stated in ASTM C1437 – 07 [21]. The testing process is started by placing the flow mold at the center of flow table. Followingly, the mortar mix is filled in layer by layer. Each layer is, compressed 20 times using tamper. After the mold is completely filled, surplus mortar is cut off to a plane surface. Then, the mold is removed and the table is instantly dropped 25 times in 15 seconds. Lastly, the diameter of the mortar spread is determined and the results are recorded. Fig. 4 illustrate the flow table testing in progress. Compressive strength and water absorption of mortar produced using diverse content of CTP were done on hardened mortar cubes in accordance with ASTM C109M-20 [22] and ASTM C642 [23] respectively. Samples were placed in water curing before the testing. Compressive test were done at 7 and 28 days utilizing compressive strength testing machine as displayed in Fig. 5.

(a) (b)

Fig. 4 *(a) Flow table test equipment (b) Testing in progress*

(a) (b)

Fig. 5 *(a) Mortar cubes; (b) Compressive strength in progress*

3. Results and Discussion

This section presents the result on the pozzolanic reactivity of ceramic tile waste and performance of mortar produced using diverse content of CTP. On overall, the integration of ground ceramic tile influenced the properties of mortar mixes.

3.1 Pozzolanic Activity

Fig 6 displays the SAI for the compressive strength of CTP mortar. The inclusion of suitable content of CTP significantly enhances the strength of the mortar. Mortars containing a maximum of 10% CTP exhibited a compressive strength activity index of 105.31% at the 28-day mark. Furthermore, it is worth mentioning that the mortar containing 20% CTP showed a significant increase in the SAI, achieving a value of 101.5%. This exceeds the ASTM C618 [18] standard's minimum threshold. However, when the CTP content exceeds 30%, the SAI of the mortar decline below the specified threshold of 75%, resulting in failure to meet the criteria prescribed in ASTM C618 [18]. After the concentration of CTP reaches 50%, the SAI declines to a value of 59.49%. This decrease can be due to the constrained development of the main calcium silicate hydrate structure in the matrix. Overall, the CTP used in this study demonstrates favorable reactivity, as demonstrated by its impact on the SAI of the mortar.

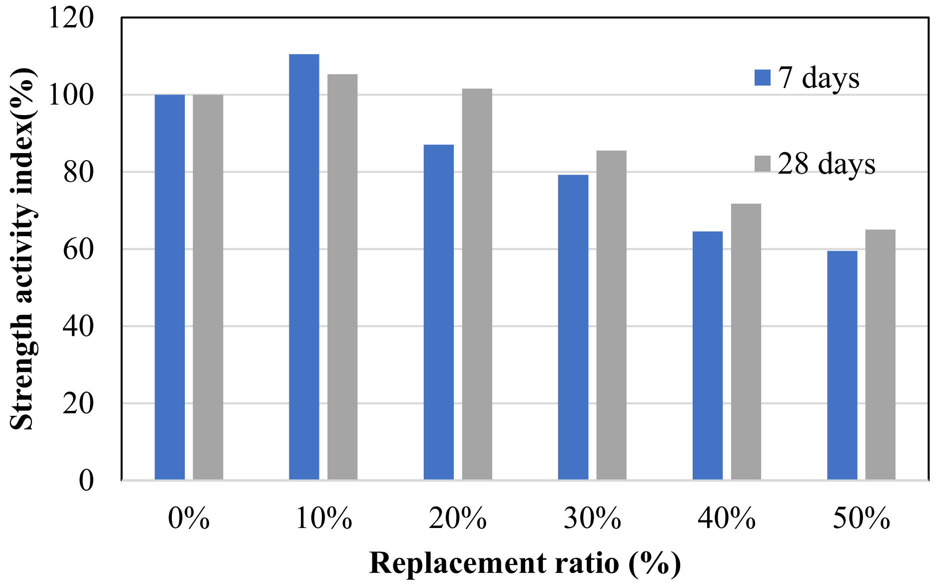

Fig. 6 *Strength activity index test results of ceramic tile powder*

3.2 Setting Time

The Fig 7 shows that the setting time becomes longer as larger quantity of CTP is blended in the mix. The initial setting time for cement paste of 0%, 10%, 20%, 30%, 40% and 50% is 79 min, 85 min, 108 min, 110 min, 133 min and 160 min respectively. At a replacement ratio of 20% and more, the utilization of CTP causes a drastic increase in the setting time of the cement paste. The dilution effect could also explain the sharp increase in setting time, especially the initial setting time (up to 2 h 40 at 50% replacement). Overall, all mixes fulfil the requirement in ASTM C1157-08a [24]. Similar pattern in terms of longer time for final setting of mixes with larger content of CTP is observed. However, all the mixes recorded final setting time which is not more than 6.5 hours as highlighted in State Bureau of Quality and Technical Supervision [25].

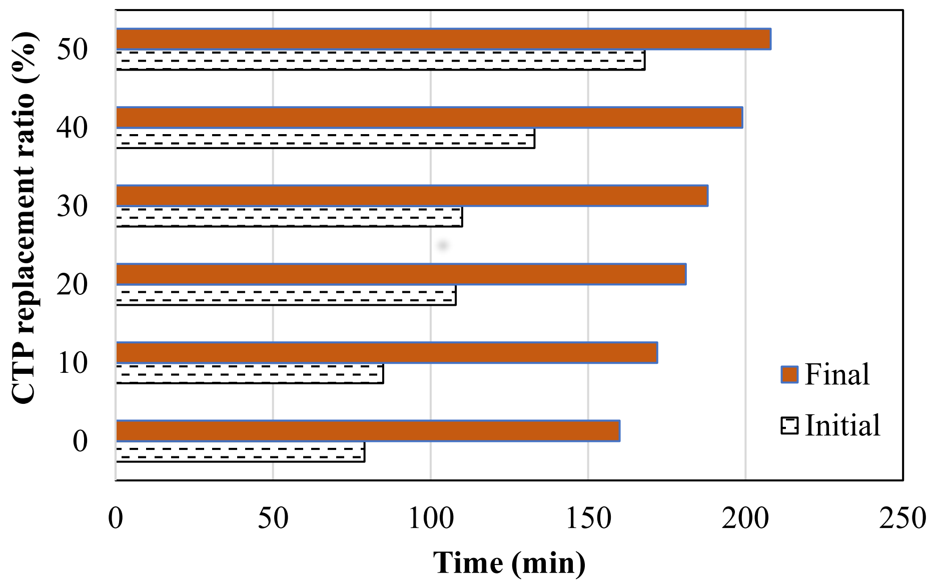

Fig. 7 *Setting time result*

3.3 Flowability

Fig. 8 illustrates the changes in flow properties observed when CTP is blended in mortar compositions. The flow characteristics of the mortars show a decrease as the amount of CTP used increases. The flow diameters of mortars with diverse percentages of 0%, 10%, 20%, 30%, 40% and 50% were measured to be 190 mm, 185 mm, 180 mm, 175 mm, 170 mm and 165 mm respectively. The blending of CTP which possesses a higher surface area compared to cement increase the water requirement of the mortar mixture. Previous researcher, Manjunath et al. [26] has pointed out the effect of using material which is finer than cement as partial cement replacement towards reduction of mortar flowability. Irregular shaped CTP intensify the friction amongst the particles leading to more force are needed to initiate the flow of the mixture. Previous researchers Mas et al. [27] and de Matos et al. [28] have also documented similar behavior in several types of cement-based composites.

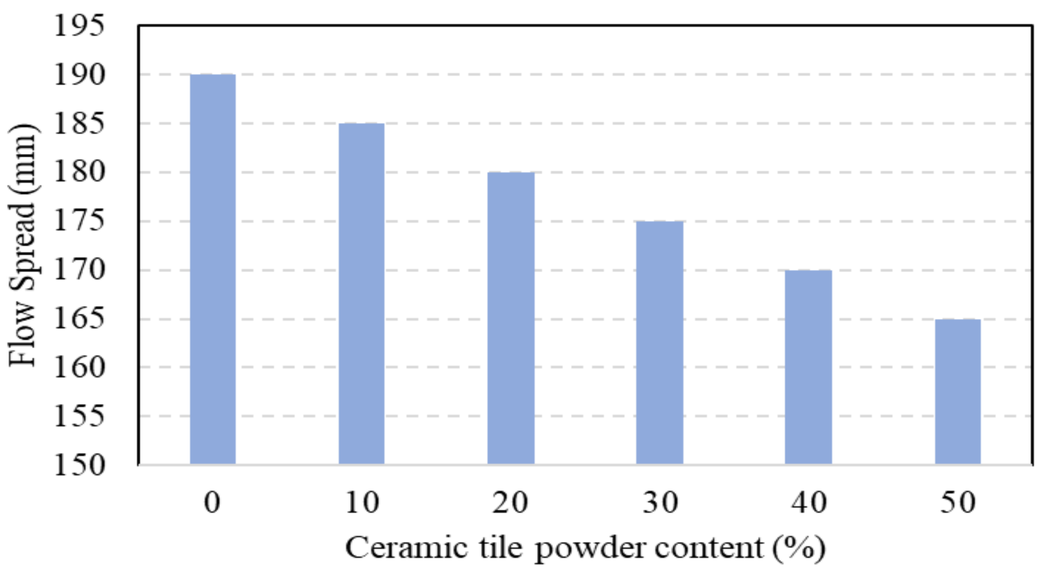

Fig. 8 *Influence of CTP content on flowability of mortar*

3.4 Compressive Strength

The compressive strength results for the mortar specimens are illustrated in Fig 9. After cured for 7 days, it is worth noting that the specimens containing 10% CTP had the maximum strength of 28.92 MPa amongst all mixes. The significant growth in compressive strength at the initial phases can be owing to high specific surface area of CTP which beneficial filling effect. In contrast, several studies have found a decrease in compressive strength at an early age compared to the control group [29, 30]. It is worth noting that the CTP used in this study has a larger specific surface area (1380 kg/m^3) than the ceramic tile powder used in the previous studies mentioned above, resulting in a stronger filling effect. However, when the replacement rate exceeded 10%, specimens experience a considerable strength decline. The reduction in strength can be owing to the combined influence of cement dilution and the absence of pozzolanic reaction induced by CTP during the early stages of hardening. After a period of 14 days, the specimens with CTP concentrations of 10% and 20% exhibited strength of 37.9 MPa and 35.08 MPa respectively, higher than the control specimen. The observed rise in compressive strength can be owing to the combined influence of the filling action and the pozzolanic reactivity provided by CTP. After 28 days, the specimens containing 10% and 20% CTP exhibited compressive values of 40.51 MPa and 39.5 MPa correspondingly, which exceeded the compressive strengths observed in the reference specimens. Nevertheless, it was shown that the compressive strength declined as the replacement rate exceeded 20%. The observed decrease can be owing to the phenomenon known as the dilution effect. A comparable pattern was recorded by Muthusamy et al. [31] and Bahurudeen et al. [32] who integrated high volume of pozzolanic ash in cement-based composite

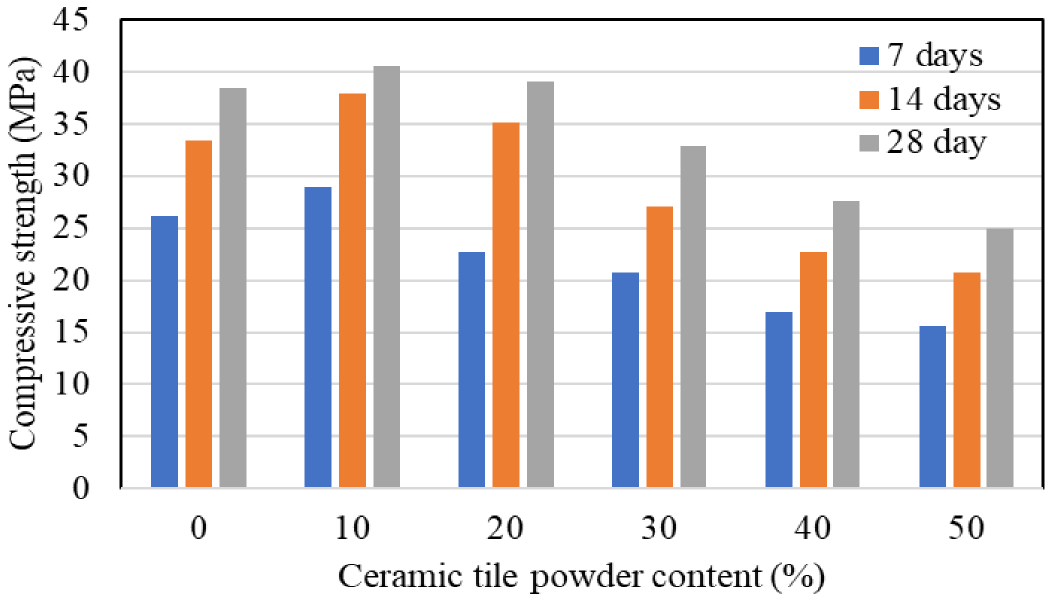

Fig. 9 *Compressive strength of mortar containing diverse content of ceramic tile powder*

The experimental test data for 7-day, 14- day and 28-day compressive strength of all mixes are given in table 3. The study investigated how two variables, curing age and the proportion replacement of CTP for cement, impact the compressive strength of CTP mortar. Through ANOVA analysis, it was determined that curing age and CTP content significantly affect compressive strength. Table 4 highlights a p-value of 0.0088, suggesting the model's significance. Moreover, a strong relationship was observed between compressive strength and these factors, represented by an R^2 value of 0.9188. Fig. 10 illustrates the correlation between various CTP content percentages and curing ages concerning the compressive strength of mortar specimens.

Table 3 *Experimental results of the designed tests*

Factor 1	Factor 2								
Ceramic tile powder	7 -days Compressive strength			14 – days compressive strength			28 – days compressive strength		
	R1*	R2	R3	R1	R2	R3	R1	R2	R3
10	27.8	28.7	30.2	34.8	38.3	40.7	38.9	39.8	42.7
20	23.5	23.8	20.9	33.9	35.2	35.9	38.6	38.4	40.0
30	21.7	20.4	20.0	26.8	27.7	26.1	32.2	31.9	34.5
40	17.4	18.2	14.9	22.8	23.0	22.5	27.5	28.1	27.1
50	14.2	15.2	16.8	19.6	21.0	21.4	25.2	24.9	24.8

** Reading 1*

Table 4 *Model validation for compressive strength of mortar*

Models	Std. Deviation	R^2	Predicted R^2	P-Value	Remarks
Linear	3.55	0.8197	0.7507	<0.0001	-
Quadratic	2.66	0.9188	0.8148	0.0088	Suggested
Cubic	1.46	0.9816	0.8554	0.0029	-

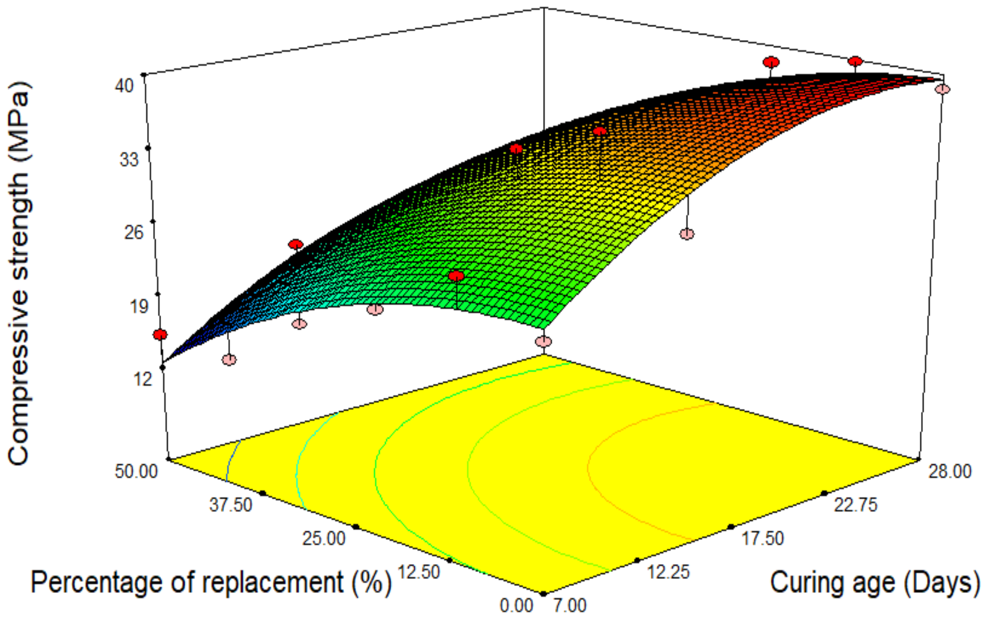

Fig. 10 *Response surface plot indicating effects of curing age and CTP content on compressive strength of mortar*

3.5 Water Absorption

The penetration of water into mortar causes inconvenience in practice. Therefore, one of the key properties of mortar is its ability to prevent water penetration [33]. The water absorption of mortar mixtures that cured for 28 days in this study are revealed in Fig. 11. Compared to the reference mix, the mortar mixes that replaced up to 20 % CTP showed almost identical values for water absorption. Owing to the pozzolanic reactivity and the filling effect of CTP, the resistance of the mortar to water absorption is the same or greater at corresponding CTP concentrations. However, an exchange ratio of more than 20 % was associated with increased water absorption, which is mainly owing to the prevailing dilution effect at a higher exchange of cement with CTP. These results are consistent with earlier publications by Nasr et al. [34] and Sondarva et al. [35].

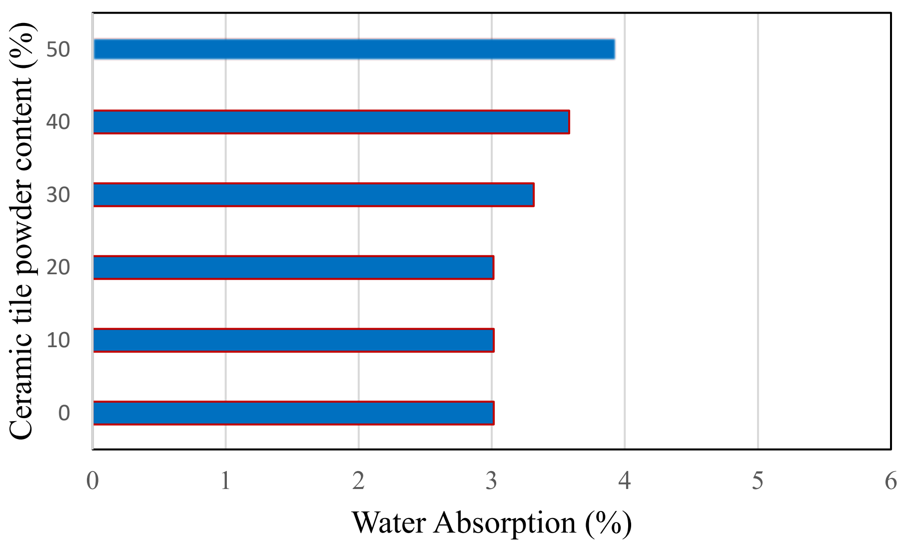

Fig. 11 *Water absorption of mortar consisting different percentage of ceramic tile powder*

4. Conclusion

The inclusion of adequate amount of CTP at 10% and 20% as cement replacement forms a workable mortar mixture and successfully enhances the mortar's compressive strength. Perfect blend of 10% CTP forms mortar with the highest strength value which is 40.51MPa amongst all mixes The strength enhancement is due to the pozzolanic reaction that increases the quantity of total CSH gel contributing to densification of the internal structure of mortar. In addition, the water absorption value of mortar with 10% and 20% as a cement replacement is comparable to that of the control mix. Excessive use CTP up to 50% is less than 4%. in the production of mortars is not recommended, as this practice results in a substantial strength declination of 25MPa. The successful incorporation of CTP in the manufacture of building products would have several benefits, including the preservation of cement resources and reduction of ceramic tile surplus that would otherwise be disposed of in landfill. Conclusion, the approach of recycling industrial waste for production of green construction material is in line with SDG12 (Responsible Consumption and Production) and SDG13 (Climate Action).

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Alaa Omar Tanash, Khairunisa Muthusamy;* ***data collection:*** *Alaa Omar Tanash;* ***analysis and interpretation of results:*** *Alaa Omar Tanash, Khairunisa Muthusamy, Mohamed A. Ismail, Nor Hazurina Othman;* ***draft manuscript preparation:*** *Alaa Omar Tanash, Khairunisa Muthusamy. All authors reviewed the results and approved the final version of the manuscript.*

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