Cleaner Engineering and Technology 17 (2023) 100699

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

A review on the utilization of ceramic tile waste as cement and aggregates replacement in cement based composite and a bibliometric assessment

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ARTICLE INFO

Keywords:
Ceramic tile waste
Cement replacement
Aggregate replacement
Sustainable concrete
Mechanical properties
Durability properties

ABSTRACT

The scientific community recognizes that the depletion of natural resources and solid waste management pose inherent challenges in building material production and disposal, particularly in concrete manufacture and deconstruction. Recycling and reusing construction waste is proposed as a solution to these issues in the literature. Repurposing waste materials as additives in concrete represents an alternative approach. For instance, ceramic tile waste (CTW) may replace a portion of the aggregate and cement used in concrete. This study extensively examines the literature on cement-based composites that utilize CTW in lieu of cement and aggregate. A thorough evaluation of mechanical, durability, and fresh properties is conducted. The physical and chemical attributes of CTW are based on extensive scientific research. Prior studies suggest that the use of ceramic tile aggregate (CTA) to concrete in the appropriate proportions could enhance its durability and strength. Finely ground ceramic tile powder (CTP) with high silica content can potentially enhance the strength and durability of concrete, according to prior research studies. The impact of CTP on the chemical resistance, drying shrinkage and fire resistance abilities of concrete are subsequently evaluated. Employing waste materials as a concrete component in a circular economy to promote environmental protection and the development of sustainable cities and communities has received broad support from the academic community.

1. Introduction

Concrete is one of the most broadly utilized materials in the construction of buildings and other infrastructure owing to its excellent mechanical properties (Liu and Chen, 2014; Shoukry et al., 2011), durability (Afroughsabet and Ozbakkaloglu, 2015; Faried et al., 2021), and fire resistance (Haido et al., 2021; Kodur, 2014; Kodur et al., 2008). Every year, over 21 Giga tons of concrete are produced worldwide (Klee, 2004; Zhang et al., 2019). The expansion of various industries to meet the demand of a diverse population with unique needs forms continuous increase in construction business. The thriving construction industry has positively boosted the concrete trade. The annual increase in concrete consumption owing to the rising demand for this product has caused a significant strain on the supply of its essential mixing ingredients (Al-Jabri et al., 2009; Aprianti et al., 2015; Behera et al., 2014; Gallagher and Peduzzi, 2019). Cement as one of the utmost important constituents that functions as a binding agent to form solid hardened concrete, is also continuously being produced in increasing volume over the years. In 2020, the cement production reached 4.3 gigaton (IEA, 2021). Global cement production is forecasted to rise by 23% by 2050 (WBCSD, 2018). Cement production poses significant environmental, economic, and social challenges in attaining the United Nations Sustainable Development Goals settled by the United Nations. Goals for Sustainable, Resilient, and Inclusive Development (SDGs) have been adopted on a worldwide scale as a means to this end (Neshovski, 2018). One of the primary desires of the SDGs is to fight climate change and its impacts. Meanwhile, this industry accounts for up to 7% of global carbon dioxide emissions (Ahmed et al., 2021; Talaei et al., 2019). This industry is the third-largest emitter of CO_2 (Andrew, 2018). The cement industry contributes 2.7 giga tons of CO_2 to the atmosphere (Mainz, 2021). In

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https://doi.org/10.1016/j.clet.2023.100699
Received 28 May 2023; Received in revised form 27 October 2023; Accepted 14 November 2023

addition, various pollutants such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), and dust/fine particulate matter (PM) are emitted into the atmosphere due to the cement production (Isaiah et al., 2021; Tanash and Muthusamy, 2022). These pollutants have adverse effects on several environmental categories, including global warming, depletion of ozone layer, and acidification of water and soil. Non-renewable energy consumption of 3–5 MJ is required to dry, crush, and sinter 1 kg of carbonate minerals into "clinker," which is then grinded into cement powder and combined with other components (Bourtsalas et al., 2018; Hendriks et al., 1998; Venkatarama Reddy and Jagadish, 2003). The production of a sustainable, more environmentally friendly, and less expensive cement material is necessary in light of growing concerns about man-made global warming, and increasing energy shortages (Lasseuguette et al., 2019). Thus, the approach of transforming the available waste materials generated from any industries as ingredients in cement production would reduce the burden at landfill, create cleaner environment and contribute towards preservation of green environment for healthier lifestyle of the nation.

The flourishing construction projects to meet the demand of diverse industries also generates waste that need to be managed. Construction and remediation activities generate significant amounts of construction waste, which accounts for a substantial portion of man-made waste (Wu et al., 2023a). The improper disposal of this waste has significant adverse effects on the environment and society and causes great concern among professionals. Construction and demolition waste (CDW) are a significant waste stream (Tanash et al., 2023). In many regions of the world, CDW accounts for about 50% of landfilled waste. In the U.S. and Europe, municipal waste management has resulted in recycling rates of 70% and 90%, respectively (Villoria Sáez and Osmani, 2019). However, in many countries, municipal waste management has failed, and recycling rates are below 10% (Hoang et al., 2020; Nunes and Mahler, 2020). In relation to that, ceramic waste which is among the waste derived from construction and demolition activities, when disposed of at dumpsites, causes environmental pollution. Ceramic products are an essential part of the building fabric used in most structures. Clay, silica, metal oxides, carbides, and other earthy elements are the principal constituents of ceramics (Mustafi et al., 2011; Pacheco-Torgal and Jalali, 2010; Subedi, 2013). Floor tiles, wall tiles, sanitary ware and household ceramics are all examples of commonly manufactured ceramics (Awoyera et al., 2018; Juan et al., 2010; Monfort et al., 2014). In 2019, the world production size of ceramic tile was about 12.6 billion m^2 (insights, 2021), which increased to 18.2 billion m^2 in 2021 (Pompo, 2021). It has been predicted that up to 30% of all ceramic production will go to waste (Agrawal et al., 2020; Mohit et al., 2021; Tan et al., 2011; Umar et al., 2021). Although some of this waste can be recycled on site (e.g., to fill excavation pits), the vast majority is disposed of in disorganized piles and landfills (Horňáková et al., 2020; Lu et al., 2020; Raval et al., 2013). It has been predicted that more than 45% of CDW arinsights, 2021e ceramic (Reig et al., 2013; Zimbili et al., 2014). Ceramic materials are inherently brittle, so handling and fixing them at construction sites produces fragments that become waste. A considerable amount of CTW is generated from demolition material and production defects every year (Pitarch et al., 2021b). Fig. 1 shows the source of ceramic tile waste, mainly from the production phase, construction, and demolition phases. Additionally, throwing of CTW in landfills can lead to contamination of soil, air, and groundwater (Aly et al., 2018; Kanaan and EL-Dieb, 2016; Tabak et al., 2012). The undesirable negative effects of CTW on the environment have been pointed out by previous researchers (Bignozzi and Saccani, 2012; El-Dieb et al., 2018; Pitarch et al., 2021b). The fact that CTW is not decomposable has led to long-term problems such as illegal dumping, environmental pollution and health problems. Hence, it is necessary to explore effective management for CTW in order to avoid environmental problems that may arise from the improper disposal of CTW (Ray et al., 2021c; Singh and Srivastava, 2018; Suzuki et al., 2009). The environmental impact of cement and CTW can be minimized by reusing this waste in concrete, which is a fascinating and sustainable green solution. The approach of diverting the CTW from the dumpsite and channelling it for concrete production positively in line with circular economy that contributes towards saving space of the precious land for better use rather than waste disposal area and reduce the hassle of waste management by the building industry. Sustainable building materials that use CTW might cut down on construction expenses, energy usage, and pollution, all while reducing the amount of raw resources needed (Matias et al., 2014; Pacheco-Torgal and Jalali, 2010).

The objective of this paper is to provide a comprehensive review of research published in various peer-reviewed sources on the extensive use of ceramic tile waste (CTW) as a substitute for natural aggregates (coarse and fine) and cement in cement-based composites. This paper provides a concise summary of a wide range of literature on the use of CTW. The literature addresses, among other topics, the evaluation of mechanical properties and durability, as well as microstructural characteristics. This review also provides a brief analysis of reported conflicting results. Therefore, this discussion focuses on the general trends, the impact of integrating CTW on various properties of concrete and mortar, potential areas for future research, and claims related to these factors in light of current developments. The goal is to promote the widespread use of CTW in the upcoming construction sector.

2. Keywords co-occurrence analysis.

1.1. Methodology

For bibliometric analysis, two databases are mainly recognized: Web of Science (WoS) and Scopus. In this study, the Scopus database was selected because it provides a broader content of summaries and citations of literature searches, mainly focused on scientific and technical disciplines. This database allows measuring the influence of research,

Fig. 1. Source of ceramic tile waste.

among other research results, and establishing a relationship between fields. The documents that were found using search query are listed in Table 1. Quarry 1 means the use of ceramic waste in the cementitious composite, while Quarry 2 means the use of ceramic waste as a substitute for cement in the cementitious composite. The preliminary phase consisted in collecting the data in different steps. In order to create an appropriate framework for the study, representative keywords were chosen that formed two queries. Data refining techniques were used to eliminate unnecessary records. Table 2 shows the numerous choices made during the data retrieval from Scopus. The articles that were produced after applying these restrictions (as illustrated in Table 2) were then saved in comma-separated values (CSV) files for analysis.

The VOS viewer (version: 1.6.19) was used to examine the data that had been gathered in more detail. Researchers strongly advise using the open-source software application VOS viewer, which is widely used in a variety of domains (Goulden et al., 2017; Van Eck and Waltman, 2010; Yang et al., 2022). The retrieved CSV files were imported into the VOS viewer, which analysed them in phases while guaranteeing the homogeneity and consistency of the data. During the VOS viewer evaluation, co-occurrence of keywords was examined.

1.2. Yearly publication trend

The annual publication trend for the searched keywords is shown in Fig. 2. The earliest article found is from 2000, and only 68 articles were published until 2013. Thereafter, the total number of publications increased slowly but steadily, reaching a total of 20 publications in 2013. However, from 2014 to September −2023, the number of publications increased significantly and reached 640. Regarding the utilize of ceramic waste as a cement substitute, the earliest article found is from 2007, and only 8 articles were published by 2015. After that, the total number of publications increased slowly but steadily, reaching a total of 34 publications in 2017. However, from 2017 to September −2023, the number of publications increased significantly and reached 162. It is interesting to note that recently, research has focused more on ceramic waste in concrete, one of the components of concrete. These findings suggested researchers are becoming more enthusiastic about green practices in the construction industry.

1.3. Keywords co-occurrence of ceramic waste in concrete

Keywords are essential research instruments because they identify and denote the crucial subjects of a field of study. The VOS viewer analysis revealed that the five most frequently occurring keywords are compressive strength, ceramic materials, ceramic waste, aggregates, and recycling. Fig. 3 Displays the global map of the co-occurrence of the keywords used by the authors in query 1 (ceramic waste in concrete). Only terms with at least 30 occurrences are considered; 49 terms meet this criterion. The co-occurrence visualization in Fig. 3 shows keyword maps, their links, and the density associated with their co-occurrence. The size of the frame of a keyword in Fig. 3 represents the frequency of its occurrence, while its position represents the frequency of its occurrence with another term. It was found 16 keywords in cluster 1 (red), 15 keywords in cluster 2 (green), 11 keywords in cluster 3 (blue), and 7 keywords in cluster 4 (yellow). The first cluster refers to the use of ceramic waste as a binder in various types of concrete. Key terms in this cluster include "compressive strength," "ceramic waste," "Portland cement," "fly ash," and "slags". The second cluster could refer to the use of ceramic waste as an aggregate of concrete. This cluster contains expressions such as "ceramic materials," "recycled," "concrete," "aggregates," and "recycled aggregates". The third cluster could refer to the various mechanical and durability properties of concrete. This cluster includes terms such as "concrete aggregate", "water absorption", "mechanical properties", "durability" and "tensile strength". Since sustainability comprises a smaller group of keywords, it is considered as one cluster, yellow coloured. In this case, cluster #4 has two closely tied keywords "sustainable development", "sustainability".

Table 1
Several resulting data from database search (Scopus) as of (2003-end of September 2023).

Query number	Article results	Article results after employing limits
1	1064	640
2	302	162

Table 2
limits/filters used when obtaining data from the Scopus database.

Option	Limits applied
Type of document	Article Review
Language	English
Source type	Journal
Subject area	Engineering Material science Environmental science
Years	2003–2023

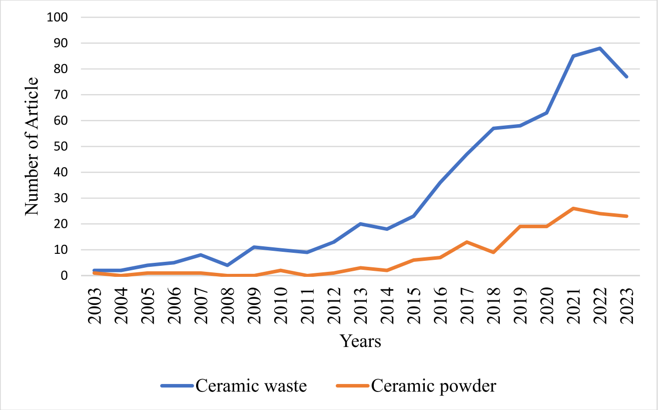


Fig. 2. Annual publication trend in the use of ceramic waste in concrete (2003-end of September 2023).

Fig. 4 shows the world map of authors who used the same keywords in response to query 2 (ceramic powder in concrete). 41 terms meet the threshold for inclusion, which is set at 10 occurrences each. There were 17 keywords in group 1 (red), 10 in group 2 (green), 9 in group 3 (blue) and 5 in group 4 (yellow). In the first group, represented here by the colour red (Group 1), the terms "compressive strength", "ceramic," and "ceramic powder" predominate. Group 2, in green, includes terms such as "fly ash," "slags," "Portland cement," and "concrete," indicating a focus on the utilize of ceramic powder as a replacement for binders in a variety of concrete types. Terms such as "powder," "ceramic waste powder," and "mortar" appear in blue Group No. 3.Finally, the terms "ceramic materials", "durability" and "concrete" are appearing in the yellow group.

2. Ceramic tile waste as aggregate replacement

2.1. Physical properties of ceramic waste aggregates

The physical, mechanical, and chemical properties of CTA play a critical role in increasing the strength and durability of concrete. The properties of the above materials are listed in Table 3. Compared to natural coarse aggregate (NCA), CTA have a lower bulk density and specific gravity. The CTA had a lower density compared to NCA and its porosity was greater, resulting in increased water absorption compared to NCA. As seen in the table, the bulk densities of the coarse CTA were within the range of 1280–1920 kg/m^3 specified by the American

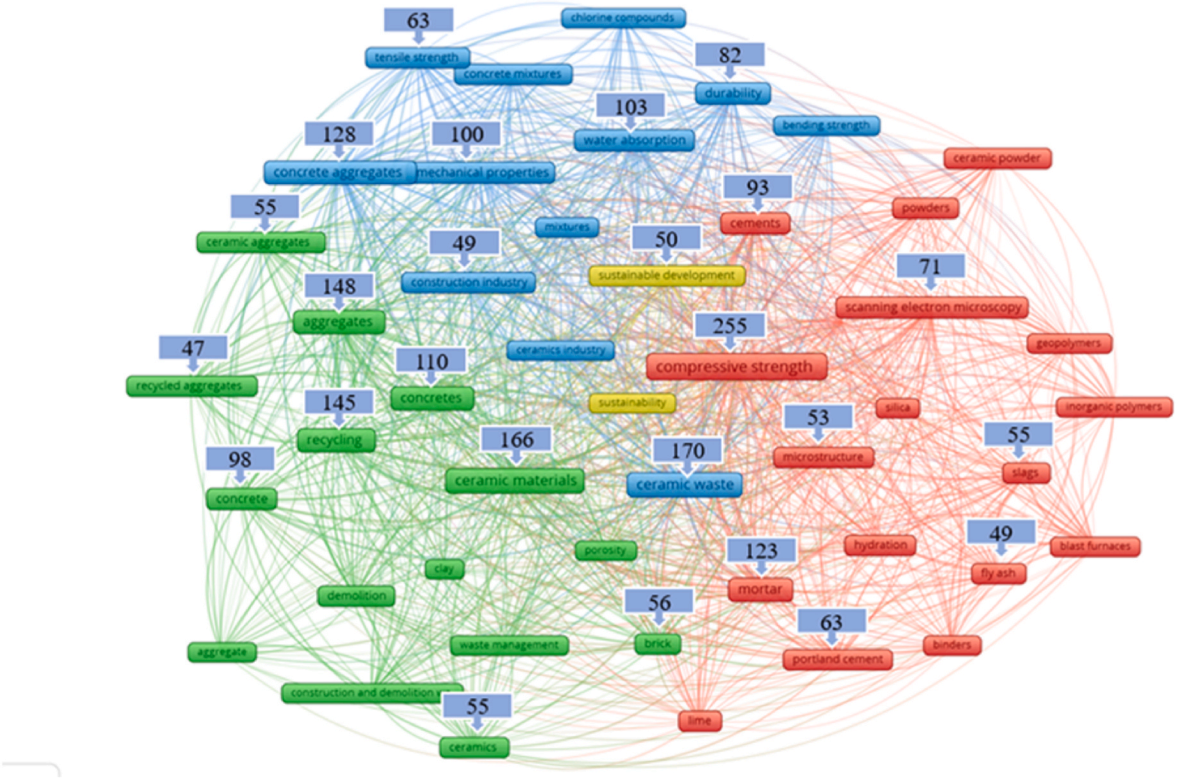


Fig. 3. Literature network of authors co-occurrence keywords for the utilize of ceramic waste in concrete (Network visualization).

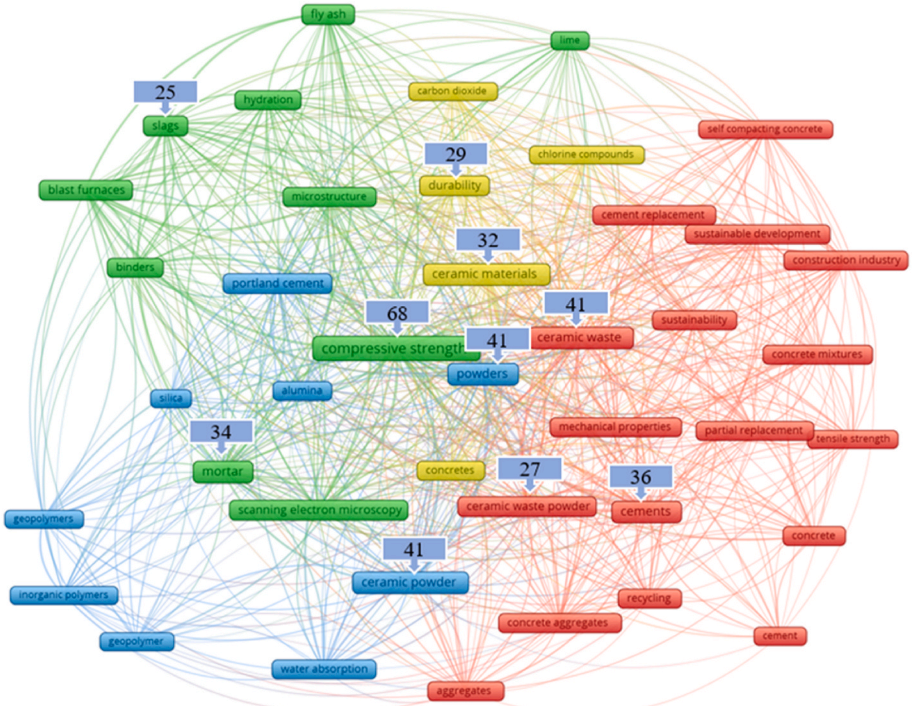


Fig. 4. Literature network of authors co-occurrence keywords for the utilize of ceramic powder in concrete (Network visualization).

Concrete Institute (ACI) for standard aggregates. The water absorption of CTA varies from 0.55% to 14.4%, and the porous nature of the CTA is the cause of the significant water absorption. The water absorption of CTA is higher than that of most NCA, i.e., less than 2% (Neville and Brooks, 1987). However, it had a lower absorption capacity compared to alternative waste materials. The differences in the physical properties of CTA are mainly due to the different firing temperatures and the different compositions of the tiles (Elçi, 2016).The angular shape of CTA is recognizable (as seen in Fig. 5), and its surface texture was found to be rougher compared to NCA. The observed cracks are a result of the

Table 3
The physical properties of CTA.

Physical property	Value range	References
Coarse aggregate		
Bulk density (Kg/m^3)	975	(Li et al., 2023a)
	1217–1265	(Daniyal and Ahmad, 2015; Mohammed and Ahmed, 2020; Nepomuceno et al., 2018; Pitarch et al., 2019; Yiosese et al., 2018)
	1323–1400	(Amin et al., 2020; Ikponmwosa and Ehikhuenmen, 2017; Daniyal and Ahmad, 2015; Mohammed and Ahmed, 2020)
	1435–1470	(Sua-iam and Jamnam, 2023; Zhang et al., 2023)
Specific gravity	2.15–2.35	(Awoyera et al., 2016; Awoyera et al., 2017b; Xu et al., 2023; Daniyal and Ahmad, 2015; Ikponmwosa and Ehikhuenmen, 2017; Mohammed and Ahmed, 2020; Singh and Singla, 2015; Sivakumar et al., 2022a; Tavakoli et al., 2013; Yiosese et al., 2018)
	2.35–2.55	(Keshavarz and Mostofinejad, 2019b; Sua-iam and Jamnam, 2023; Umapathy et al., 2014)
	2.55–2.75	(Goyal, et al., 2022; Sekar, 2017)
Crushing value (%)	9.5–14.33	(Daniyal and Ahmad, 2015; Mohammed and Ahmed, 2020; Awoyera et al., 2017b; Ikponmwosa and Ehikhuenmen, 2017; Awoyera et al., 2016; Li et al., 2023a)
	20–27.6	(Sivakumar et al., 2022a; Anderson et al., 2016; Sekar, 2017; Amin et al., 2020; Sua-iam and Jamnam, 2023; Tavakoli et al., 2013)
	28–35.4	(Goyal et al., 2022; Nepomuceno et al., 2018)
Impact value (%)	12.5–18.5	(Manikandan, et al., 2023; Sekar, 2017; Sivakumar et al., 2022a; Tavakoli et al., 2013)
	20–24.2	(Awoyera et al., 2017b; Goyal et al., 2022; Singh and Singla, 2015)
	25–27.00	(Amin et al., 2020; Awoyera et al., 2016; Umapathy et al., 2014)
Water absorption (%)	0.18–2.7	(Ikponmwosa and Ehikhuenmen, 2017; Sivakumar et al., 2022a; Amin et al., 2020; Awoyera et al., 2016; Awoyera et al., 2017b; Goyal, R.K. et al., 2022; Keshavarz and Mostofinejad, 2019b; Sua-iam and Jamnam, 2023)
	4.5–9.8	(Daniyal and Ahmad, 2015; Mohammed and Ahmed, 2020; Anderson et al., 2016; Li et al., 2023a; Pitarch et al., 2019; Xu et al., 2023; Yiosese et al., 2018)
	11.5–16.6	(Nepomuceno et al., 2018; Singh and Singla, 2015; Zareei et al., 2019b)
Fine aggregate		
Specific gravity	2.26–2.37	(Awoyera et al., 2021; Meena et al., 2022d, 2023)
	2.43–2.55	(Sivakumar et al., 2022a; Vilas Meena et al., 2022; Zhang et al., 2023)
	2.65	Ramirez et al. (2023)
Water absorption (%)	.19–2.51	(Manikandan, et al., 2023; Meena et al., 2023; Vilas Meena et al., 2022b; Sivakumar et al., 2022a; Vilas Meena et al., 2022; Awoyera et al., 2021; Meena et al., 2022d)
	8.46	Ramirez et al. (2023)
	9.60	Zhang et al. (2023)

crushing process (Sua-iam and Jamnam, 2023; Torkittikul and Chaipanich, 2010). As shown in Fig. 6, pores can be easily identified in both wall and floor tile aggregates, with the pore size of wall tile aggregates being significantly larger than that of natural coarse aggregates.

2.2. Workability

Fig. 7 shows the effect of CTA as coarse and fine aggregate on the workability of cement-based composite material.In general, the workability of cement-based composite with CTA decreases when the proportion of CTA substituting for natural aggregate (NA) increases (Al Bakri et al., 2013; Anderson et al., 2016; Awoyera et al., 2016; Awoyera et al., 2021; Azmi et al., 2017; Gharibi and Mostofinejad, 2023; Giridhar et al., 2015; Gour et al., 2022; Hilal et al., 2020; Jackiewicz-Rek et al., 2015; Johnson Daniel and Sangeetha, 2021; Martínez-Lage et al., 2012; Medina et al., 2012; Vilas Meena et al., 2022e; Mohammadhosseini et al., 2020a; Ramirez et al., 2023; Rashid et al., 2017; Ray et al., 2021a; Sivakumar et al., 2022a; Sua-iam and Jamnam, 2023; Tassew and Lubell, 2014; Torkittikul and Chaipanich, 2010; Yiosese et al., 2018; Zareei et al., 2019b; Zhang et al., 2023). The deterioration in workability can be attributed to the greater roughness and irregular shape of the CTA surface compared to NA. The workability of cement-based composites is reduced due to the interlocking of the CTA because of the increased frictional resistance (Meena et al., 2022d; Mohammadhosseini et al., 2020a; Torkittikul and Chaipanich, 2010; Zhang et al., 2023).In addition, the porous nature of CTA increases the ability of the mixture to absorb water (Anderson et al., 2016; Awoyera et al., 2021; Hilal et al., 2020; Zareei et al., 2019b; Zhang et al., 2023). According to Alves et al. (2014), increasing the water-cement ratio is an effective way to overcome the decrease in workability. In addition, the adverse effects on the workability of the cement-based composite can be mitigated by pre-soaking CTA with some of the appropriate water, thereby achieving saturation of CTA (Paul et al., 2023; Roig-Flores et al., 2023).

2.3. Fresh and dry densities

The collective results of several studies have revealed a consensus regarding the effects of increasing CTA content on the density of cement-based composites. It was found that with increasing CTA replacement, there is a corresponding linear decrease in fresh and dry density (Daniyal and Ahmad, 2015; Elçi, 2016; Gharibi and Mostofinejad, 2023; Hilal et al., 2020; Pitarch et al., 2019; Poon and Chan, 2007; Sharba, 2020; Subedi et al., 2020; Tabak et al., 2012; Zareei et al., 2019a). Density decreases as the substitution ratio of NA to CTA increases. This can be explained by the lower density of CTA compared to NA. In addition, the uneven and rough shape of CTA leads to a higher percentage of voids (Hilal et al., 2020; Goyal et al., 2022). A literature search showed a reduction in fresh density of 14%–20% when comparing CTA blends to a control blend (Elçi, 2016; Hilal et al., 2020). Similarly, when neutral coarse aggregate (NCA) is completely replaced by the coarse CTA, the dry density experiences a reduction from 2260 kg/m^3 (for 0% replacement) to 1670 kg/m^3 (Elçi, 2016). In addition, other studies reported a decreasing trend in dry density of cement-based composites when replaced by CTA (Goyal et al., 2022; Ikponmwosa and Ehikhuenmen, 2017; Poon and Chan, 2007).

2.4. Compressive strength

In studies using concrete with CTA, compressive strength was the most important mechanical behaviour investigated. Fig. 8 illustrates the compressive strength performance of cement-based composite upon the inclusion of CTA as coarse aggregate replacement. The compressive strength of concrete often comparable or increase when coarse CTA are included (Anderson et al., 2016; Awoyera et al., 2018; Daniyal and Ahmad, 2015; Goyal et al., 2022; Manikandan et al., 2023; Rashid et al., 2017; Roig-Flores et al., 2023; Subedi et al., 2020; Varma and Pravalli, 2022; Xu et al., 2022a; Yiosese et al., 2018). Fig. 10 illustrates the change in 28-day compressive strength of concrete including CTA as NCA replacement. Several studies have shown that the use of coarse CTA as a replacement for NCA in the range of 5%–30% results in a significant improvement in compressive strength from 5% to 25% (Awoyera et al., 2018; Daniyal and Ahmad, 2015; Goyal et al., 2022; Rashid et al., 2017; Subedi et al., 2020; Varma and Pravalli, 2022; Zareei et al., 2019a). The observed increase in 28 days compressive strength can be attributed to the irregular morphology and coarse texture of CTA, which allows more effective interlocking between the aggregates and the hardened cement paste (Awoyera et al., 2018; Zareei et al., 2019a). In addition, it should be noted that CTA, as a permeable substance, provides a moist

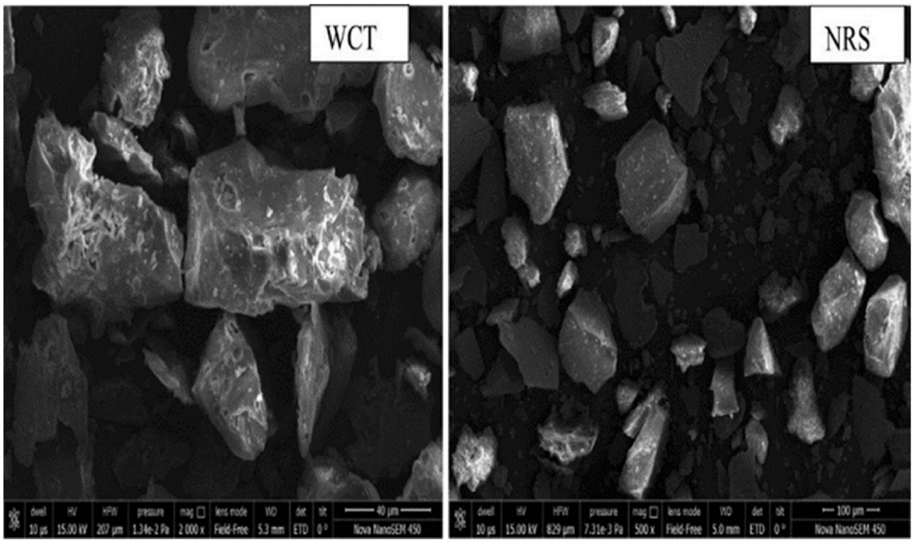
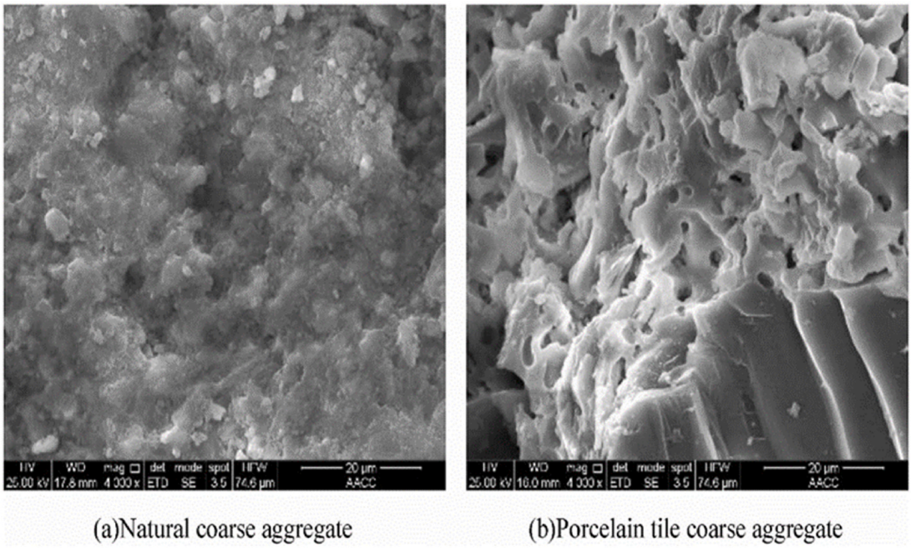


Fig. 5. The SEM image of fine CTA and natural sand. Adapted from (Meena et al., 2022d).



(a)Natural coarse aggregate

(b)Porcelain tile coarse aggregate

Fig. 6. SEM results of coarse CTA. (Adapted from (Li, et al., 2023)).

environment for the hydration process of the cement paste. This property leads to a reduction in autogenous shrinkage, which ultimately leads to an increase in the compressive strength of the cement-based composite (Rashid et al., 2017; Suzuki et al., 2009a; Xu et al., 2022a; Yiosese et al., 2018).

Similarly, the optimal use of fine CTA increases the 28-day compressive strength of the cement-based composite. Fig. 9 illustrates the change in 28-day compressive strength of concrete including fine CTA as a function of the proportion of aggregate replaced. The use of fine CTA as a substitute for natural fine aggregate (NFA) at levels up to 60% generally results in higher compressive strength compared to conventional concrete, with compressive strength increasing by 5–30% after 28 days (Abadou et al., 2016; Guendouz and Boukhelkhal, 2019; Meena et al., 2022a, 2022d; Zhang et al., 2023). It could be that the increased compressive strength of cement-based composites with CTA is due to the irregular shape and rough surface of the particles (Gharibi and Mostofinejad, 2023; Vilas Meena et al., 2022b; Meena et al., 2022d). Another reason for the increase in compressive strength is the presence of water in the fine CTA. This allows sufficient hydration of the cement by internal curing, which leads to improved hydration of the cement and thus to better properties of the cement-based composite (Gonzalez-Corominas and Etxeberria, 2014; Suzuki et al., 2009; Zhang et al., 2023). The improvement in compressive strength can be attributed in part to the pozzolanic properties of fine CTA (Awoyera et al., 2021; Manikandan et al., 2023; Vilas Meena et al., 2022b). In addition, the mixture with fine CTA was better compacted due to the uniform particle size distribution and high content of very fine CTA particles, which improved particle packing (Evangelista et al., 2019b; Vilas Meena et al., 2022b; Vilas Meena et al., 2022e).

2.5. Splitting tensile strength

The change in 28-day splitting tensile strength of concrete with coarse CTA, as a function of the proportion of replaced aggregates, is shown in Fig. 10. Replacement of NCA with coarse CTA in the range of 5%–40% often results in higher 28-day splitting tensile strength compared to conventional concrete, with increases ranging from 3% to 21%.This increase in 28-day splitting tensile strength could be related to the same factors that influence the increase in compressive strength: 1) irregular morphology and coarse texture of CTA 2) CTA is a permeable

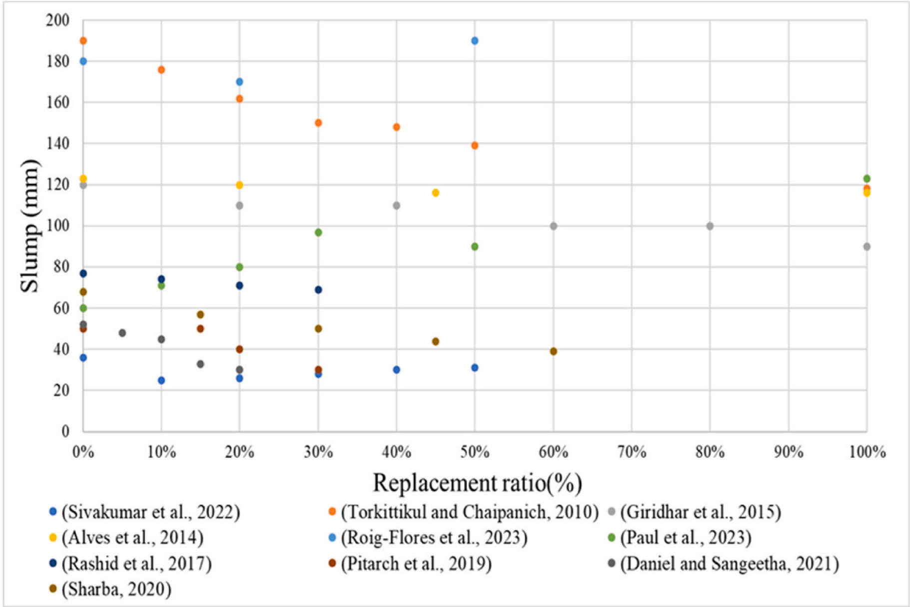


Fig. 7. The effect of CTA as a substitute for fine or coarse aggregates on the workability of cement-based composite. (Adapted from (Alves et al., 2014; Daniel and Sangeetha, 2021; Giridhar et al., 2015; Paul et al., 2023; Pitarch et al., 2019; Rashid et al., 2017; Roig-Flores et al., 2023; Sharba, 2020; Sivakumar et al., 2022; Torkittikul and Chaipanich, 2010)).

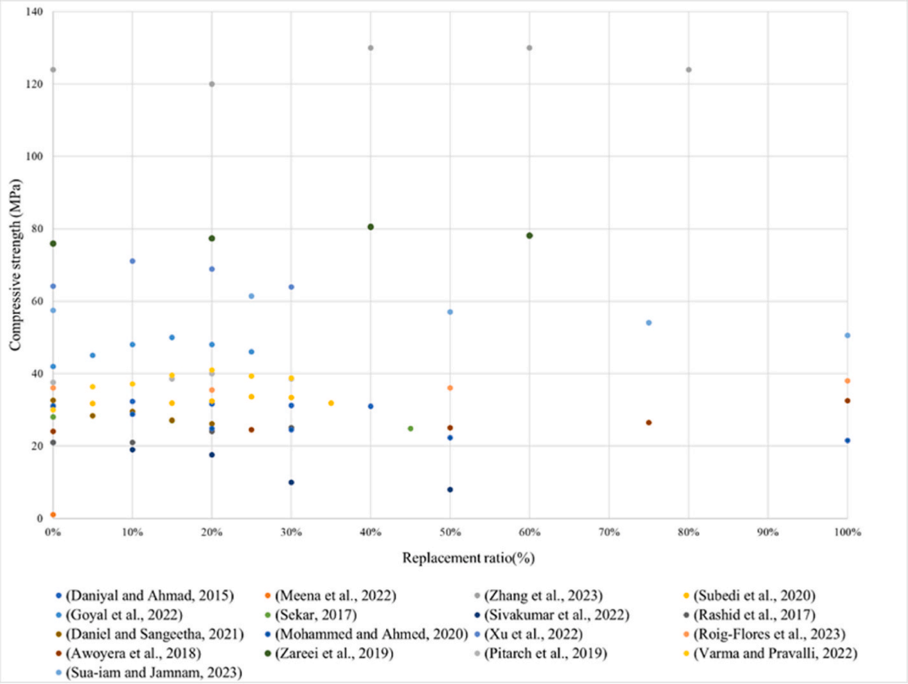


Fig. 8. The effect of CTA as a substitute for coarse aggregates on the compressive strength of cement-based composite (Adapted from (Awoyera et al., 2018; Daniel and Sangeetha, 2021; Daniyal and Ahmad, 2015; Goyal et al., 2022; Meena et al., 2022a; Mohammed and Ahmed, 2020; Pitarch et al., 2019; Rashid et al., 2017; Roig-Flores et al., 2023; Sekar, 2017; Sivakumar et al., 2022a; Sua-iam and Jamnam, 2023; Subedi et al., 2020; Varma and Pravalli, 2022; Xu et al., 2022a; Zareei et al., 2019a; Zhang et al., 2023)).

substance that provides a moist environment. In addition, This may be attributed to the fact that incorporating coarse CTA refines the pore system, resulting in an increase in the volume of capillary pores and a decrease in the volume of macropores (Awoyera et al., 2018; Medina et al., 2012). On the other hand, the splitting tensile strength shows a comparable or slightly lower with an increasing replacement ratio of more than 50% (Anderson et al., 2016; Mohammed and Ahmed, 2020).

On the other hand, The change in 28-day splitting tensile strength of concrete with fine CTA, as a function of the proportion of replaced NFA, is shown in Fig. 11 several studies in the literature have documented a remarkable improvement in splitting tensile strength when CTA is incorporated as a fine aggregate (Awoyera et al., 2018; Boopathi, 2023; Meena et al., 2022a; Meena et al., 2022d; Ray et al., 2021a; Shareef et al., 2023). Several studies show that the use of 60% CTA as a substitute for NFA results in a significant increase in compressive strength, ranging from 5% to 30% (Boopathi, 2023; Vilas Meena et al., 2022b;

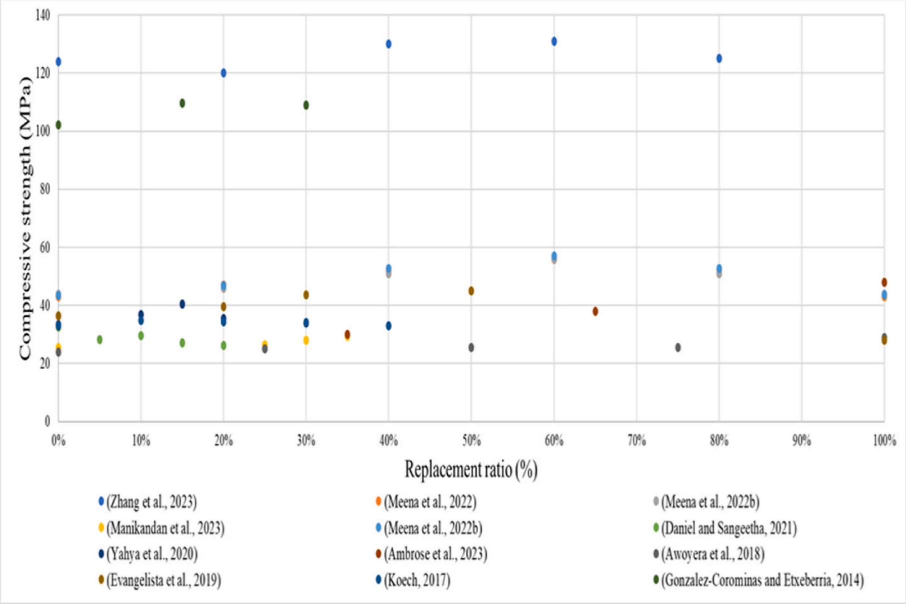


Fig. 9. The effect of CTA as a substitute for fine aggregates on the 28 days compressive strength of cement-based composite (Adapted from (Ambrose et al., 2023; Awoyera et al., 2018; Daniel and Sangeetha, 2021; Evangelista et al., 2019a; Gonzalez-Corominas and Etxeberria, 2014; Koech, 2017; Manikandan et al., 2023; Meena et al., 2022a; Meena et al., 2022c, d; Yahya et al., 2020; Zhang et al., 2023)).

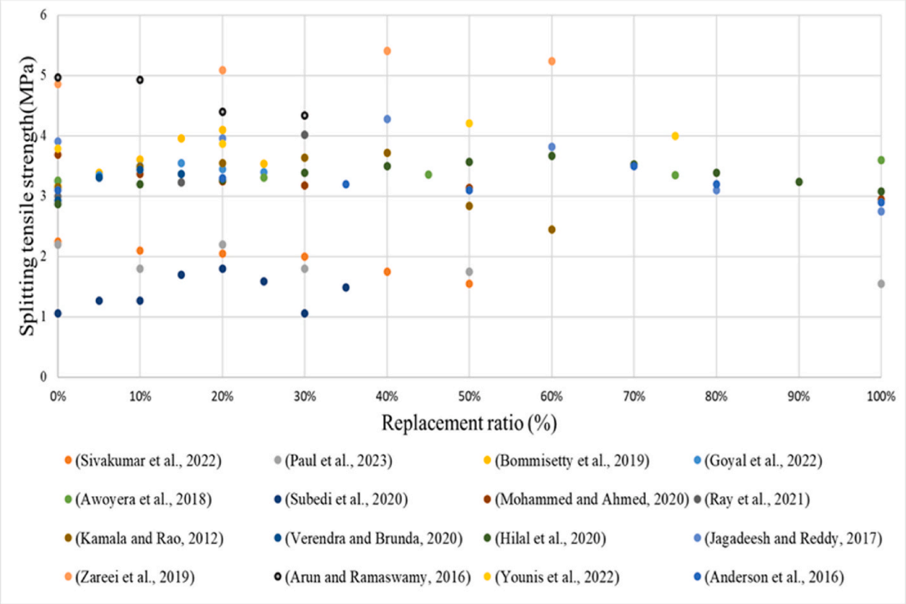


Fig. 10. The effect of CTA as a substitute for coarse aggregates on the splitting tensile strength of cement-based composite. (Adapted from (Anderson et al., 2016; Arun and Ramaswamy, 2016; Awoyera et al., 2018; Bommisetty et al., 2019; Goyal et al., 2022; Hilal et al., 2020; Jagadeesh and Reddy, 2017; Kamala and Rao, 2012; Mohammed and Ahmed, 2020; Paul et al., 2023; Sivakumar et al., 2022a; Subedi et al., 2020; Verendra and Brunda, 2020; Younis et al., 2022; Zareei et al., 2019a)).

Meena et al., 2022d). With increasing fine CTA content, the strength increase during the curing time also increases. It was found that the splitting tensile strength increased by up to 30% when 50% of the NFA was replaced by fine CTA (Awoyera et al., 2018; Boopathi, 2023; Evangelista et al., 2019b; Ray et al., 2021a). The optimum replacement level of NFA by CTA was found to be in the range of 20–60%, further than the compressive strength reduces gradually (Awoyera et al., 2018; Boopathi, 2023; Evangelista et al., 2019b; Vilas Meena et al., 2022b; Meena et al., 2022d; Ray et al., 2021c).It is worth mentioning that the fine CTA has a higher fineness modulus than the (NFA). This leads to a densification of the mixture and to a reduction of the macropores, ensuring a sufficient strength development.

2.6. Flexural strength

The change in 28-day flexural strength of concrete with coarse CTA, as a function of the proportion of CTA, is shown in Fig. 12. Several studies have reported that the use of CTA as a 20% replacement for NCA has comparable or even higher flexural strength compared to conventional concrete (Agrawal et al., 2020; Anderson et al., 2016; Bommisetty et al., 2019; Chandel and Goyal, 2022; Goyal et al., 2022; Kamala and Rao, 2012; Mohammed and Ahmed, 2020; Sivakumar et al., 2022;

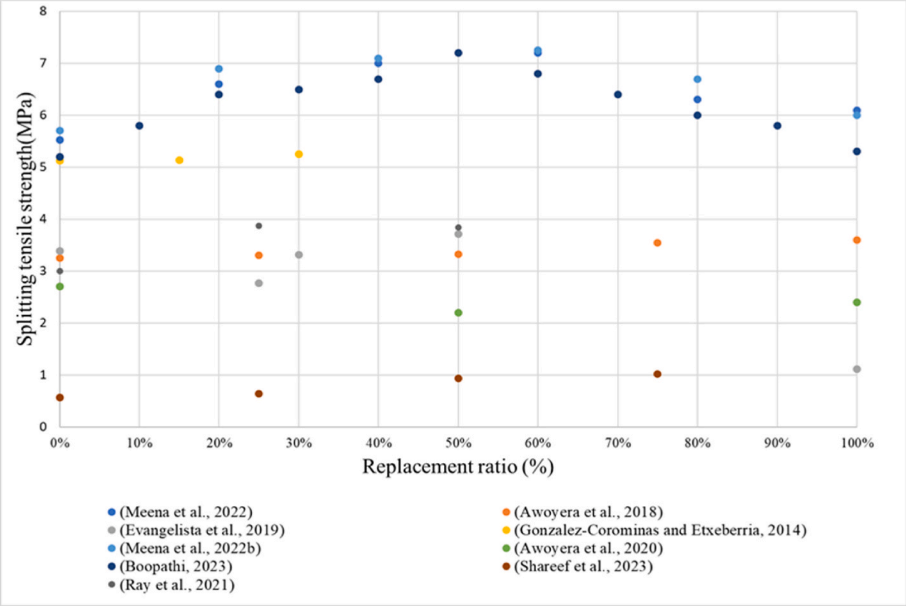


Fig. 11. The effect of CTA as a substitute for fine aggregates on the splitting tensile strength of cement-based composite. (Adapted from (Awoyera et al., 2018; Awoyera et al., 2018; Boopathi, 2023; Evangelista et al., 2019a; Gonzalez-Corominas and Etxeberria, 2014; Meena et al., 2022a; Meena et al., 2022d; Ray et al., 2021c; Shareef et al., 2023)).

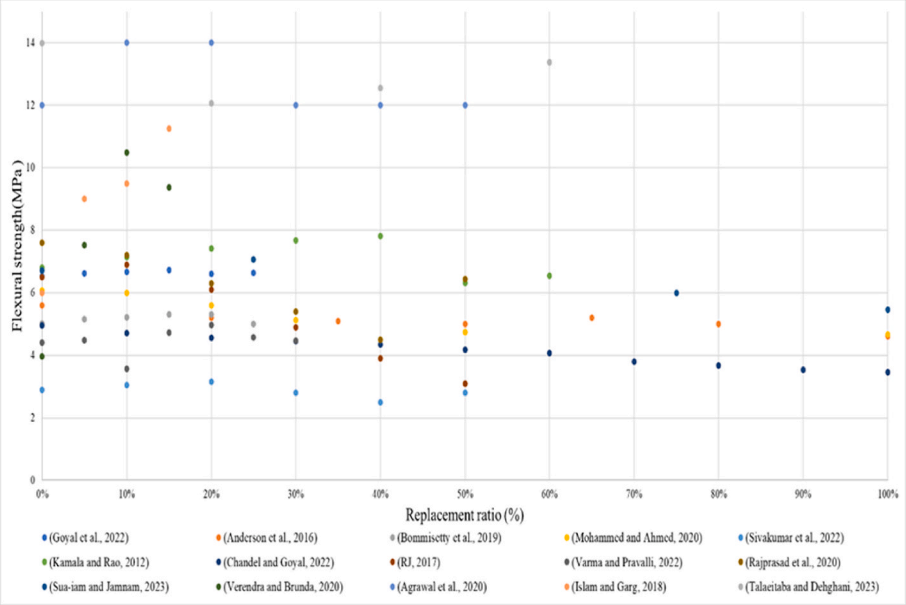


Fig. 12. The effect of CTA as a substitute for coarse aggregates on the 28 days flexural strength of cement-based composite (Adapted from (Anderson et al., 2016; Bommisetty et al., 2019; Chandel and Goyal, 2022; Goyal et al., 2022; Kamala and Rao, 2012; Mohammed and Ahmed, 2020; Rajprasad et al., 2020; Isah, 2017; Sivakumar et al., 2022; Sua-iam and Jamnam, 2023a; Talaeitaba and Dehghani, 2023; Varma and Pravalli, 2022; Verendra and Brunda, 2020)).

Varma and Pravalli, 2022). In addition, it is found that the flexural strength to compressive strength ratio of ultra-high-performance concrete (UHPC) with CTA shows an increasing trend with increasing curing age. This indicates that the flexural strength of UHPC with CTA increases faster compared to its compressive strength. Consequently, the toughness of the material also increases steadily with time. When the CTA content is 80%, the ratio of flexural strength to compressive strength reaches a maximum value of 0.143, which corresponds to an increase of 20% compared to the control group (Zhang et al., 2023). The ratio of flexural strength to compressive strength increases progressively with increasing CTA content. This observation shows that CTA has a more favourable effect on flexural strength compared to compressive strength.

Similarly, concrete containing fine CTA particles often exhibit better flexural strength after a 28-day curing period than concrete composed of natural fine aggregates. Fig. 13 shows the change in 28-day flexural strength of concrete with fine CTA as a function of the extent of NCA substitution. Replacing NFA with fine CTA in a proportion of 10%–60% typically leads to a boost in flexural strength when compared to standard concrete, resulting in an increase ranging from 14.2% to 45% (Boopathi, 2023; Guendouz and Boukhelkhal, 2019; Meena et al., 2022a; Meena et al., 2022d; Zhang et al., 2023).

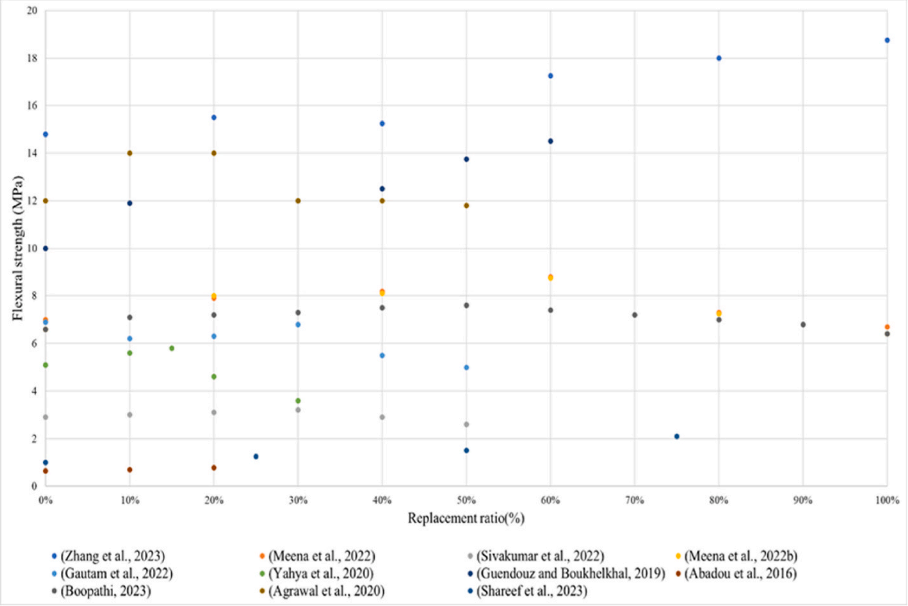


Fig. 13. The effect of CTA as a substitute for fine aggregates on the flexural strength of cement-based composite (Adapted from (Abadou et al., 2016; Agrawal et al., 2020; Boopathi, 2023; Gautam et al., 2022a; Guendouz and Boukhelkhal, 2019; Meena et al., 2022a; Meena et al., 2022d; Shareef et al., 2023; Sivakumar et al., 2022; Yahya et al., 2020; Zhang et al., 2023)).

2.7. *Modulus of elasticity*

The substitution of natural coarse aggregates by CTA has a significant effect on the elastic behaviour of cement-based composites. Fig. 14 illustrates the relationship between the percentage of aggregate replaced and the corresponding change in the 28-day modulus of elasticity of concrete with coarse CTA. In general, the elastic modulus of concrete containing CTA increases with increasing CTA content. The complete replacement of natural coarse aggregates by CTA leads to a noticeable increase in the modulus of elasticity in concrete mixtures containing CTA (Anderson et al., 2016b; Meillyta et al., 2023; Younis et al., 2022). The modulus of elasticity shows an increase of up to 26.9% compared to the control concrete, with a total replacement of 100% (Anderson et al., 2016b). The significant rise in the modulus of elasticity can be ascribed to the elevated angular morphology and textured surface of CTA in comparison to natural coarse aggregate. This increase is proportional to the replacement ratio of the aggregate, indicating a clear correlation between the modulus of elasticity and the proportion of angular aggregate (Anderson et al., 2016b). On the contrary, alternative studies have shown that the use of coarse CTA as a substitute for NCA leads to a reduction in the elastic modulus of cement-based composites (Al-Azzawi and Al-Azzawi, 2020; Li et al., 2023a; Mohan et al., 2018; Peter et al., 2020; Tahwia, 2017). The observed discrepancies in the results of the different studies can be attributed to the different physical properties of the CTA used.

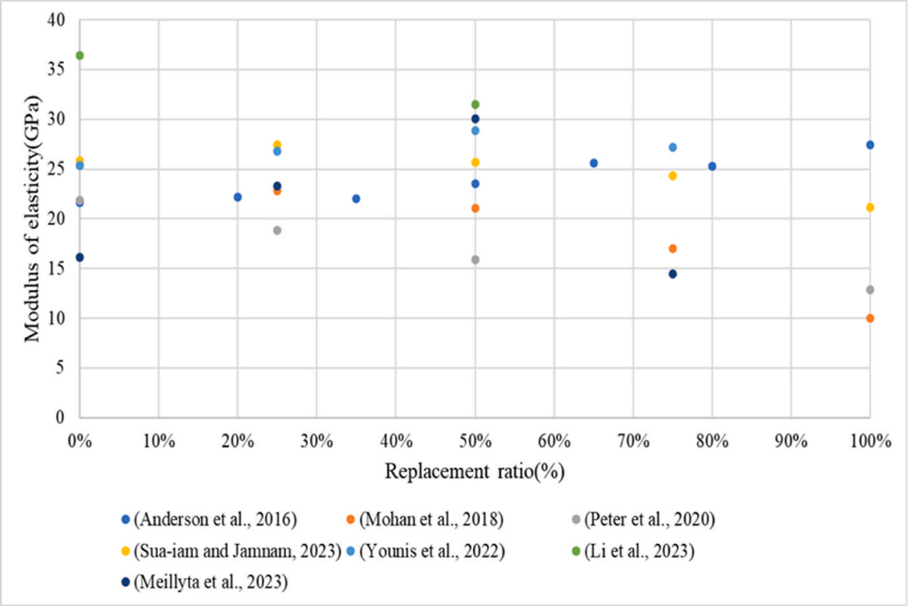


Fig. 14. The effect of CTA as a substitute for NCA on the Modulus of elasticity of cement-based composite (Adapted from (Anderson et al., 2016; Li et al., 2023; Meillyta et al., 2023; Mohan et al., 2018; Peter et al., 2020; Sua-iam and Jamnam, 2023a; Younis et al., 2022)).

3. Durability-related properties of CTA concrete

3.1. Water absorption

In this section, the water absorption properties of CTA-based cementitious composites are explained since the water absorption properties of concrete play a crucial role in determining its overall quality and strength. In several experiments it was found that increasing the proportion of CTA in the concrete increases the water absorption capacity of the concrete (Elçi, 2016; Hilal et al., 2020; Keshavarz and Mostofinejad, 2019a; Goyal et al., 2022; Paul et al., 2023; Subathra Devi et al., 2017). Using CTA as NCA replacement in concrete has been shown to dramatically increase absorption and porosity. Paul et al. (2023) reported that the absorption increases by approximately 130, 142, 150, 174, and 221% in concrete with CTA contents of 10, 20, 30, 50, and 100%, respectively, compared to the reference concrete after 28 days. The increased absorption coefficient of CTA can be attributed to its better absorption capacity compared to NCA. In addition, the increased percentage of voids in mixtures containing CTA serves as an empty vessel, which improves the ability of these mixtures to absorb a greater amount of water (Hilal et al., 2020). It is worth noting that, according to a study carried out by Amin et al. (2020), the use of mineral admixtures to replace cement effectively reduces the water absorption of ultra-high performance concrete made with coarse CTA. Furthermore, the capillary absorption of concretes made with coarse CTA showed significantly higher values compared to conventional concretes (Arun and Ramaswamy, 2016; Gonzalez-Corominas and Etxeberria, 2014). This increment is probably due to the improved interconnection of the pores in each grain of the coarse-grained aggregate mixture. On the other hand, other researchers have noted a gradual decrease in water absorption as the coarse CTA content increases, with a slight increase when the course CTA replacement level exceeds a certain threshold (Amin et al., 2021a; Nataraja et al., 2022; Roig-Flores et al., 2023; Sua-iam and Jamnam, 2023; Younis et al., 2022).Samples mixed with well-graded CTA increase filling capacity, reducing water absorption (Sivakumar et al., 2022a). Furthermore, the porous nature of CTA means that it maintains a high level of internal moisture, which in turn promotes gel formation and subsequent pore sealing (Younis et al., 2022).Therefore, the admixture of CTA as a substitute for NCA in concrete can lead to two different effects on the permeability of the cement-based composite. Fig. 15 shows the effect of CTA as a substitute for coarse aggregates on the water absorption of various types of cement-based composites.

The water absorption decreases with an increased inclusion of fine CTA as a substitute for NFA until certain threshold (Boopathi, 2023; Gautam et al., 2022b; Kherraf et al., 2022; Vilas Meena et al., 2022b; Nayana. and Rakesh, 2018). In another research, Meena et al. (2022c) reported that the use of up to 60% fine CTA resulted in lower water absorption compared with other substitutes. The results indicate a decrease in water absorption to less than 2%. A similar result was observed by Boopathi (2023), the results showed that using 50% of fine CTA reduced the water absorption of self-compacting concrete to 1.9%, and further increasing the replacement ratio slightly increased the water absorption. Other researchers found that the use of up to 20% fine CTA as NFA reduced the water absorption of various cement-based composites and increased at higher replacement ratios. This could be due to the presence of tiny CTA particles has been seen to refine the pore size, leading in a drop in the water-to-cement ratio (w/c ratio). This reduction in w/c ratio subsequently leads to a decrease in both permeability and the thickness of the interfacial transition zone (Gautam et al., 2022b; Vilas Meena et al., 2022b). In contrast, other studies have shown that the use of fine CTA enhances the water absorption of cement-based composites (Ajamul et al., 2018; Azmi et al., 2017; Guendouz and Boukhelkhal, 2019; Ramirez et al., 2023; Yahya et al., 2020). The porosity of cement-based composites is shown to increase, mostly because to the porous nature of CTA and the higher absorption capacity of CTA in comparison to NFA (Guendouz and Boukhelkhal, 2019).It can be concluded that the use of fine CTA as a substitute for NFA in cement-based composites may have two opposing influences on water absorption. Therefore, the impact of CTA on the water absorption of concrete depends on the prevalence of one effect over the other. Fig. 16 shows the effect of CTA as a substitute for fine aggregates on the water absorption of various types of cement-based composites.

3.2. Chloride diffusion

The durability of concrete structures is significantly affected by chloride-induced reinforcement corrosion. The chloride penetration resistance of concrete with coarse CTA is comparatively inferior to that

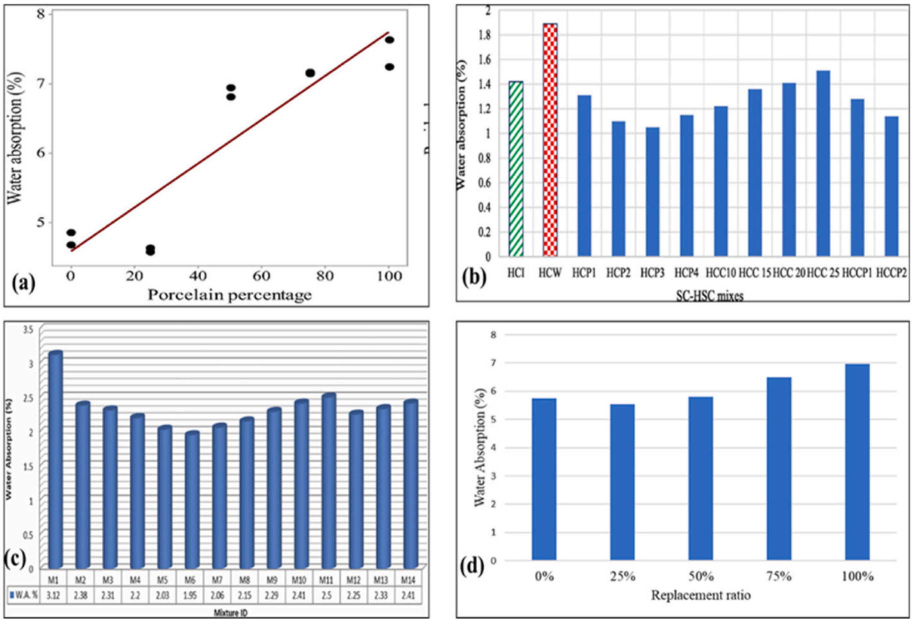


Fig. 15. The effect of CTA as a substitute for NCA on the water absorption of various types of cement-based composites a) Normal concrete (Adapted from (Keshavarz and Mostofinejad, 2019a)) b) Self curing high performance concrete (Adapted from (Amin et al., 2021)) c)self-curing normal concrete (Adapted from (Younis et al., 2022)) d) self-compacting concrete (Adapted from (Sua-iam and Jamnam, 2023)).

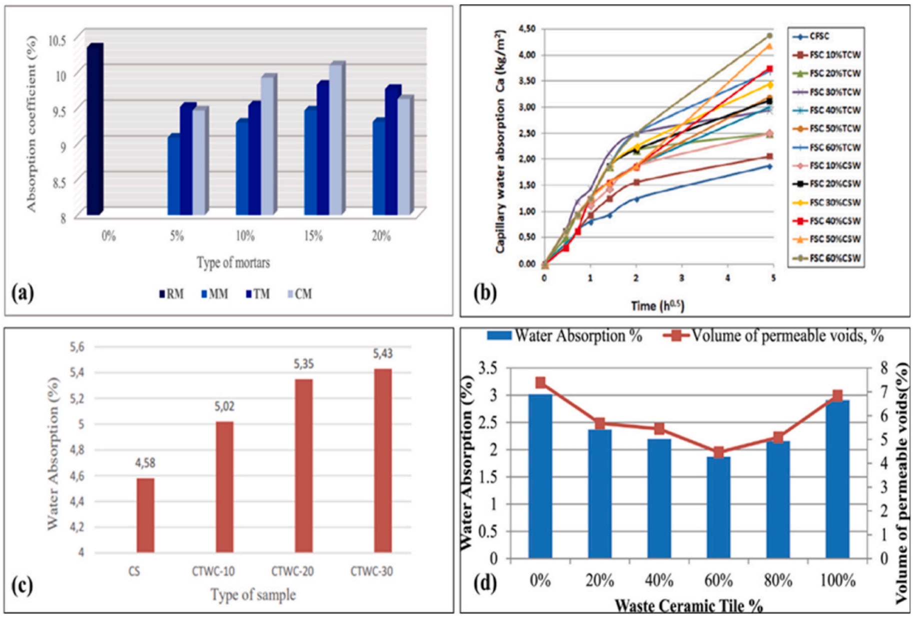


Fig. 16. The effect of CTA as a substitute for fine aggregates on the water absorption of various types of cement-based composites a) Mortar (Adapted from (Kherraf et al., 2022)) b) Flowable sand concrete (Adapted from (Guendouz and Boukhelkhal, 2019)) c) Normal concrete (Adapted from (Yahya et al., 2020)) d) self-compacting concrete (Adapted from (Meena et al., 2022a)).

of concrete with NCA (Gonzalez-Corominas and Etxeberria, 2014; Xu et al., 2023; Yasin Mousavi et al., 2020). The increase in CTA content leads to an increase in both the 'depth of critical chloride content' and the apparent chloride diffusion coefficient (Xu et al., 2023; Yasin Mousavi et al., 2020).However, it is worthy to mention that the chloride ion passed charges fall within low to moderate range as specified per ASTM. Xu et al. (2023) results indicate a significant increase in the transferred charge of the samples when coarse CTA is used as a substitute for NCA, by 10%, 20%, and 30%, with respective increases of 18.2%, 26.8%, and 53.2%.The observed phenomenon can be attributed to the increased permeability of the concrete due to high porosity coarse CTA (Xu et al., 2023; Yasin Mousavi et al., 2020). However, recent research has shown that supplementary cementitious materials (SCM) can mitigate the reduction in chloride ion resistance that results from replacing NCA with coarse CTA(Ngoc-Tra Lam et al., 2023). This observation could be attributed to the use of SCM, which led to a refinement of the pore structure of the concrete.On the other hand, alternative studies have shown that the substitution of NCA by coarse CTA leads to a reduction in chloride ion penetration (Amin et al., 2021a; Arun and Ramaswamy, 2016; Sivakumar et al., 2022a). The observed phenomenon can be attributed to the use of coarse CTA under conditions characterized by a saturated and dried surface, which mitigates the adverse consequences of the pronounced water absorption properties of CTA. Furthermore, the reduced permeability to chloride ions may be associated with the high-water absorption of coarse CTA, which is enhanced by the retention of water required for the ongoing rehydration

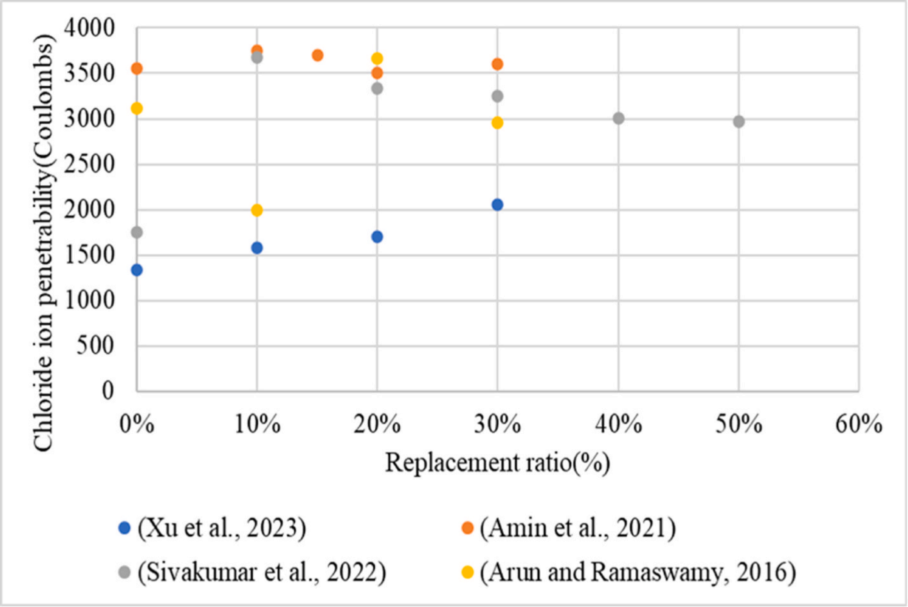


Fig. 17. The charge passed through concrete with different replacement ratios with coarse CTA (Adapted from (Amin et al., 2021a; Arun and Ramaswamy, 2016; Sivakumar et al., 2022a; Xu et al., 2023)).

process. The addition of CTA helps maintain a high internal moisture content, which facilitates the completion of hydration processes and allows for the continued formation of gel and subsequent pore closure (Amin et al., 2021). Fig. 17 shows the charge passed through concrete with different replacement ratios with coarse CTA.

The use of fine CTA as a replacement for NFA gives good results in terms of resistance to chloride ion penetration. In general, the diffusion coefficient of chloride ions decreases as the proportion of fine CTA as a fine aggregate in the concrete increases up to a certain threshold (Binici, 2007; Gonzalez-Corominas and Etxeberria, 2014; Mohammadhosseini et al., 2020a; Packrisamy and Jayakumar, 2022). The 'depth to critical chloride content' and the apparent chloride diffusion coefficient are both reduced by an increase in fine CTA level (as shown in Fig. 20) (Packrisamy and Jayakumar, 2022). The observed phenomenon can be attributed to the presence of adsorbed water in CTA may have contributed to increased hydration of the cement particles near the aggregates. This in turn could have led to the formation of a compact microstructure, reducing the permeability to chloride ions (Packrisamy and Jayakumar, 2022). In addition, the pozzolanic reactivity of fine CTA particles, which leads to a densification of the microstructure of cement-based composites and a reduction in the pore size within such composites (Mohammadhosseini et al., 2020a). The trend observed generally extends up to a replacement ratio of 40%, whereas a further increase in the replacement ratio results in an increase in the transportation of chloride ions (Packrisamy and Jayakumar, 2022). In addition, ageing of the concrete is accompanied by a decrease in chloride permeability within the CTA-based concrete. The values for total charge permeability fall below the "very low" range, indicating that the concrete is durable in terms of chloride permeability (Etxeberria and Gonzalez-Corominas, 2018; Gonzalez-Corominas and Etxeberria, 2014; Packrisamy and Jayakumar, 2022). The decrease in chloride penetration can be attributed to the impeded diffusion of chloride ions within the cement matrix around the fine CTA particles due to pozzolanic activity. Fig. 18 shows the influence of fine CTA as a substitute for natural fine aggregate on chloride diffusion behaviour.

3.3. Resistance to sulphate attack

The correlation between the increase in the fine fraction of CTA and the resistance to expansion due to sulphate attack is noted (Ambrose et al., 2023; Meena et al., 2023; Samadi et al., 2020b). The pozzolanic reaction of a part of fine CTA leads to a decrease in the formation of surplus ettringite, which is generally produced by the reaction between sulphate and calcium hydroxide (Meena et al., 2023). The diminished occurrence of secondary ettringite in concrete based on fine CTA enhances its capacity to withstand expansion resulting from sodium sulphate. In addition, the presence of CTA particles with a coarse surface and angular morphology results in favourable interlocking with the cement paste, improving resistance to attack by sulfuric acid (Meena et al., 2023). It is important to highlight that the pozzolanic activity of fine CTA supersedes the effect of increased porosity in concrete mixtures that utilize CTA, thus increasing their resilience against sulphate attack.

3.4. Drying shrinkage

Elçi (2016) reported that the use of CTA as a substitute for NCA increased the drying shrinkage of concrete. The results showed that the shrinkage value of aggregates for floor tiles and wall tiles was 1.37 and 2.42 times higher than that of control specimens, respectively. This could be attributed to the high-water absorption of CTA. In another study, Younis et al. (2022) documented the occurrence of both early and late shrinkage. The admixture of CTA as a coarse aggregate in self-curing concrete results in a reduction of drying shrinkage. The porous CTA material exhibits a phenomenon known as the "reservoir effect" In this effect, the absorbed moisture is gradually released into the concrete mix during the drying process, resulting in a reduction in shrinkage at a constant water-cement ratio. On the other hand, the use of fine CTA as a substitute for NFA showed a reduction in drying shrinkage of cement-based composites (Batikha et al., 2021; Ghrieb et al., 2021; Vilas Meena et al., 2022e; Rodríguez-Álvaro et al., 2022). The decrease in shrinkage noted indicates that the aggregates played a part in partially reducing the process of self-desiccation, which happened concurrently with external drying over a certain period. This decrease in drying shrinkage could be due to the angular particle packing of fine CTA (Vilas Meena et al., 2022e).

4. Ceramic tile powder (CTP) as cement replacement

4.1. Physical aspects

Ceramic tile waste (CTW) is available in white and red colours. The existence of a significant amount of iron oxide (Fe_2O_3) is considered to be the cause of the red colour of CTW (Monteiro et al., 2008; Pacheco-Torgal and Jalali, 2010). After being subjected to fine grinding, the particles of CTP become more uniform and acquire a rounder appearance (Pereira-de-Oliveira et al., 2012b; Xu et al., 2021) as illustrated in Fig. 19. The specific gravity of CTP is between 2.30 and 2.80. The reported physical properties of the CTP vary from one research to another owing to the differences in the grinding process adopted, e.g., the amount of material in a ball mill and the duration of grinding. Scanning electron microscope findings show that the CTP consists of angular and irregular particles resembling cement (Aly et al., 2019; Chen et al., 2022; El-Dieb and Kanaan, 2018; Kannan et al., 2017; Mohit and Sharifi, 2019). As the grain size gradation of CTP is comparable to that of cement

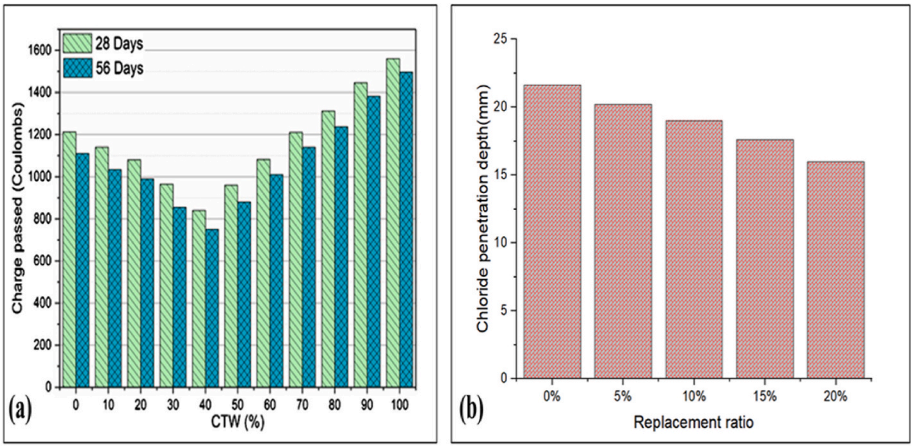


Fig. 18. The influence of fine CTA as a substitute for NFA on chloride diffusion behaviour (Adapted from (Packrisamy and Jayakumar, 2022)).

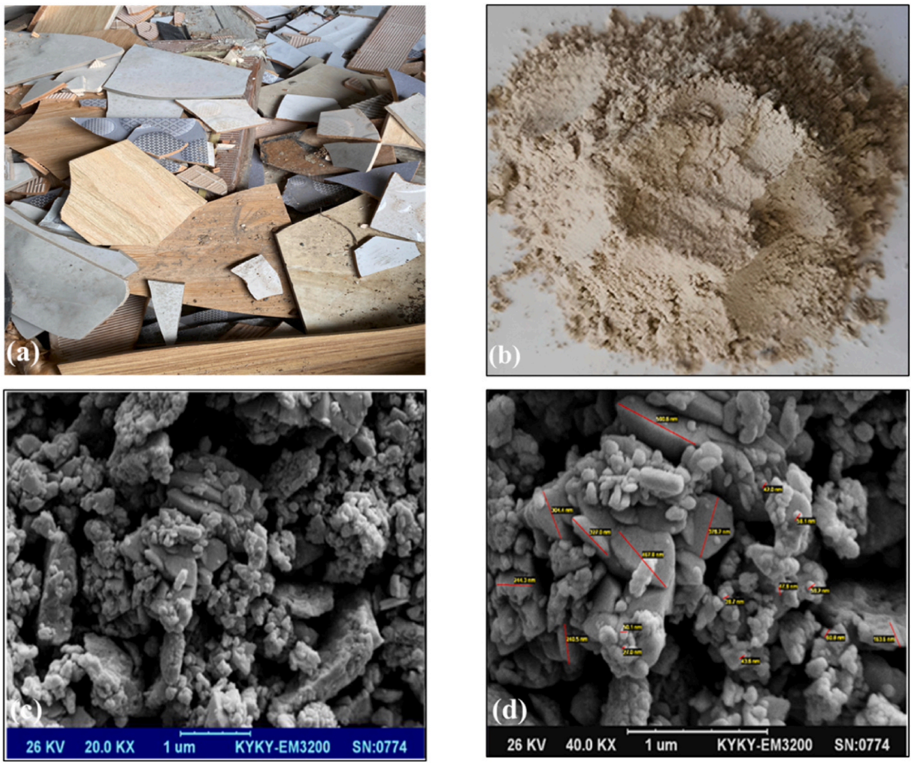


Fig. 19. (a)Ceramic tile waste at dumping site **(b)** Ceramic tile powder (Adapted from (Xu et al., 2021)) (c) SEM Image of ceramic tile powder, enlarged with 20kx (Adapted from (Mohit and Sharifi, 2019)) (d) SEM Image of ceramic tile powder, enlarged with 40kx (Adapted from (Mohit and Sharifi, 2019)) (

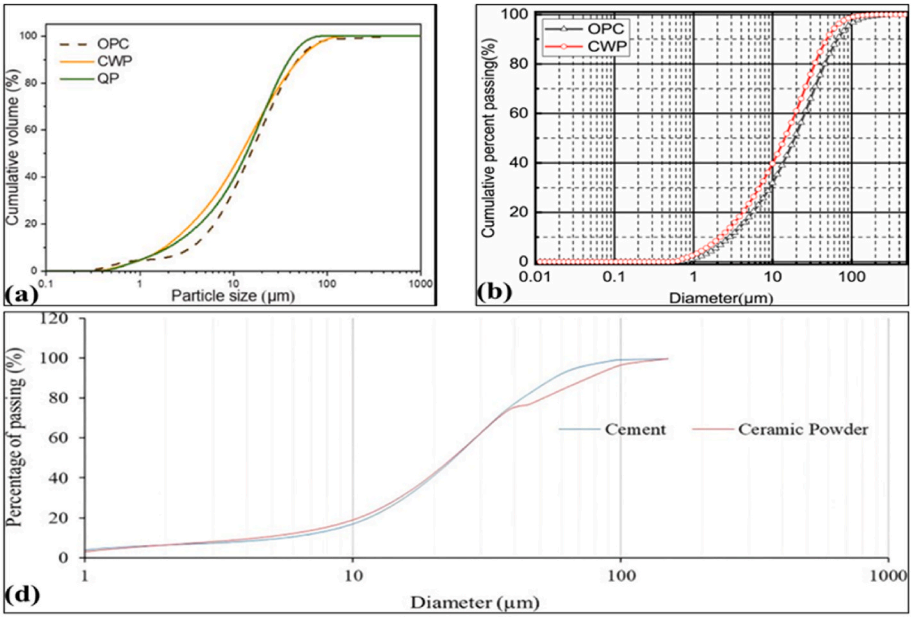


Fig. 20. The particle size distribution of CTP (Adapted from (Chen et al., 2022; Mohit et al., 2021; Ouyang et al., 2022a)).

(as illustrated in Fig. 20) (Chen et al., 2022; Gautam et al., 2021; Ouyang et al., 2022a). Fig. 19 demonstrates the appearance of CTW. Table 4 exhibits the various physical properties of CTP.

4.2. Chemical composition

The chemical composition of CTP documented in Table 5 is a compilation of data from various studies. CTP has a high content of silica and alumina. A minor amount of magnesium and alkali oxides are also identified in the CTP. Furthermore, table 5shows that sulphur trioxide is not present in significant amounts in the CTP. The reported oxide composition of the CTP differs from one researcher to another. This is owing to the properties of the feeding material used in the manufacturing process, e.g., mineralogy and chemistry (Njoya et al., 2012). The loss on ignition of CTP is below 3%. The difference in loss on ignition is, to an extent, related to the concentration of SiO_2 and Al_2O_3. Thus, the loss on ignition is higher at a higher SiO_2 and Al_2O_3 concentration, which is due to the high clay mineral content (Boussen et al.,

Table 4
Physical properties of CTP.

Reference	Specific gravity	Medium particle size, μm	Specific surface area, m^2/g
Mohit and Sharifi (2019)	2.54	<100	.554
Huseien et al. (2020)	2.6	35	12.2
Hoppe Filho et al. (2021)	2.65	28.53	12.8
Mansoori et al. (2021)	2.58	–	–
Sánchez de Rojas et al. (2014)	2.65		3
Samadi et al. (2020a)	2.35	35	–
Assaad and Mardani (2023)	2.65	21.08	.4
Ebrahimi et al. (2023)		3.33	.414
Wu et al. (2023b)	2.64		.365

2016). According to past researchers (Awoyera et al., 2017b; El-Dieb and Kanaan, 2018; Heidari et al., 2019; Hilal et al., 2021; Ouda and Gharieb, 2021), CTP has more than 70% of silica, alumina and iron oxide, which meets the requirements of ASTM 618 (Astm) enabling it to be utilized as pozzolanic material. The availability of significant amount of silica and alumina would contribute towards pozzolanic reaction and enhances the strength of concrete. The oxide composition of CTP makes it an excellent pozzolanic material (Heidari and Tavakoli, 2013; Mo et al., 2016; Sánchez de Rojas et al., 2006). These pozzolanic properties of CTP have inspired several researchers to explore the ability of CTP as a SCM to be utilized in the production of concrete in order to promote towards the achievement of sustainability.

4.3. *Workability*

The use of CTP influences the workability of concrete mixture as documented in Fig. 21. In general, the use of CTP leads to increased water demand, which increases with increasing CTP content instead of cement. This phenomenon can be attributed to the non-uniform morphology and significant water absorption properties of CTP (Awoyera et al., 2017b; de Matos et al., 2021; Hilal et al., 2020; Mas et al., 2016; Mohammadhosseini et al., 2019a; Mohammadhosseini et al., 2020b; Pereira-de-Oliveira et al., 2012b). According to de Matos et al. (2021) findings, unevenly shaped CTP particles can increase interlocking, which increases friction between the particles and subsequently increases the energy required for the mixture to flow, commonly referred to as yield stress. Furthermore, Use of finer sized CTP as compared to OPC with larger surface area, which needs more mixing water, reduces the workability of cement-based mixture. Similarly, Hilal et al. (2021) observed a decrease in the workability of mortar when CTP was used as a cement substitution. The findings showed that the workability decreased with the raise of the level and fineness of CTP relative to the control samples. This is mainly due to the fineness of the CTP used in the concrete. In general, the finer grains of the CTP densify the matrix by filling the voids and reducing the porosity of the cement-based composite. As a result, the matrix becomes stiffer with the utilize of CTP and the flowability of the cement-based composite decreases (Mohammadhosseini et al., 2020a). On the contrary, alternative studies have shown that the use of CTP as a cement replacement improves the workability of cement-based composites (Bheel et al., 2019; Nalli and Vysyaraju, 2022; Pitarch. et al., 2021; Sondarva et al., 2022). The variation in the processing methods of each researcher, especially the size of CTP used, determines the workability of the concrete mixture. Basically, the employment of grinding techniques in terms of equipment used, quantity of CTP ground at a time and grinding duration determines the particle size of CTP, which influences concrete workability.

Table 5
Chemical composition of CTP.

Ref.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	SO_3	LOI	SiO_2+ Al_2O_3+ Fe_2O_3
El-Dieb and Kanaan (2018)	68.6	17.0	0.8	1.7	2.5	0.73	–		–	12	1.78	86
Awoyera et al. (2017b)	64.5	15	6	4.18	2.04	1.45	2.00	0.88	1.04	–	–	86
Mohammadhosseini et al. (2019a)	74.10	17.8	3.58	2.00	–	–	2.65	–	–	–	.10	95
Mas et al. (2016)	61.22	18.60	5.02	5.77	1.79	13.46	3.03		.25	.09	0·70	84.84
Huseien et al. (2019)	72.6	12.2	.8	.02	0.99	.73	.03	–	–	.12	1.05	85.62
Xu et al. (2021)	78.30	15.90	–	0.90	0.80	1.45	1.55	–	–	–	1.78	94.2
Lasseuguette et al. (2019)	68.9	19.8	0.9	7	0.3	.3	1.7	–	.2	–	0.2	89.6
Pitarch et al. (2021b)	61.2	18.6	5.0	5.8	1.8	0.33	0.76	–	–	.09	.7	84.8
Heidari et al. (2019)	68.85	18.53	4.81	1.57	0.72	2.01	1.63	–	–	–	0.48	92.19
de Matos et al. (2021)	74.2	19.48	2.38	0.46	–	–	2.32	–	–	–	0.49	96.52
Samadi et al. (2015)	74.1	17.8	3.57	1.11	–	–	2.69	–	–	–	0.1	95.47
Hilal et al. (2021)	57.40	17.98	6.20	5.72	–	–	4.09	–	–	1.59	–	81
Ouda and Gharieb (2021)	60.60	26.90	2.55	5.80	0.67	0.91	0.44	–		0.22	0.51	90.05
Hoppe Filho et al. (2021)	72.20	16.20	6.29		0.82	<0.10	0.6	–	–	–	1.17	94.69
El-Kattan et al. (2020)	68.2	24.22	0.92	.63	0.19	1.65	.56	–	–	–	–	93.34
Mansoori et al. (2021)	63.48	18.6	8.62	1.38	1.35	2.32	1.66			.56		90.7
Sánchez de Rojas et al. (2014)	67.03	19.95	6.29	0.11	1.37	0.21	3.54	–	–	–	0.47	93.24
Mohit and Sharifi (2019)	64.04	21	6.51	1.29	0.88	0.57	2.35	–	–	0.11	1.1	91.51
Lim et al. (2018)	74.10	17.80	3.57	1.11	–	–	2.69	–	–	–	0.10	95.47
Sondarva et al. (2022)	60.5	28.0	1.02	4.2	.89	–	–	–	–	1.7	1.2	89.5
Chen et al. (2022)	67.83	19.68	0.86	7.42	0.34	0.22	1.73	0.67		0.04	0.18	88.73
Babatola and Arum (2020)	73.54	20.26	3.54	.75			3.96	.26		–		97.34
Najm and Ahmad (2022)	68.85	17	.82	1.7	2.5		1.63	.737		–	1.67	86.67
Praseeda and Rao (2021)	69	16.5	.5	.5	1.25	2.12	3.2	–	–	1.23	2	86
Ouyang et al. (2022a)	74.16	15.85	1.19	.85	.126	3.5	2.28	–	–	–	2.04	91.2
Ahmad and Alhayani (2022)	66.73	18.15	3.96	3.62	3.6	–	3.37	–	–	–	–	88.84
Tawfik et al. (2021)	68.6	17	.8	1.7	2.5	–	–	–	–	.12	1.78	86.4
Shamsaei et al. (2019)	71.19	15.6	3.20	3.54	1.28	1.36	1.98	–	–	0.10	0.88	90
AlArab et al. (2022)	67.3	19.8	2.5	2.3	2	–	–	–	–	0.10	–	89.6
Najm et al. (2022)	68.85	17	0.8	1.7	2.5	–	0.737	–	–	–	1.78	86.65
Mohit et al. (2023)	66	19	6	1.8	0.9	2.1	2.35	–	–	0.1	1.75	91
El-Dieb et al. (2018)	67.51	16.92	.75	1.33	1.82	4.8	1.31	–	–	–	2.54	85.81
Rashad and Essa (2020)	59.9	18.8	7.64	6.47	0.72	1.41	1.68	0.95	–	0.31	1.16	86.34
Taher et al. (2023)	61.72	22.31	1.24	6.67	0.65	0.96	1.55	–	–	0.07	3.96	85.27

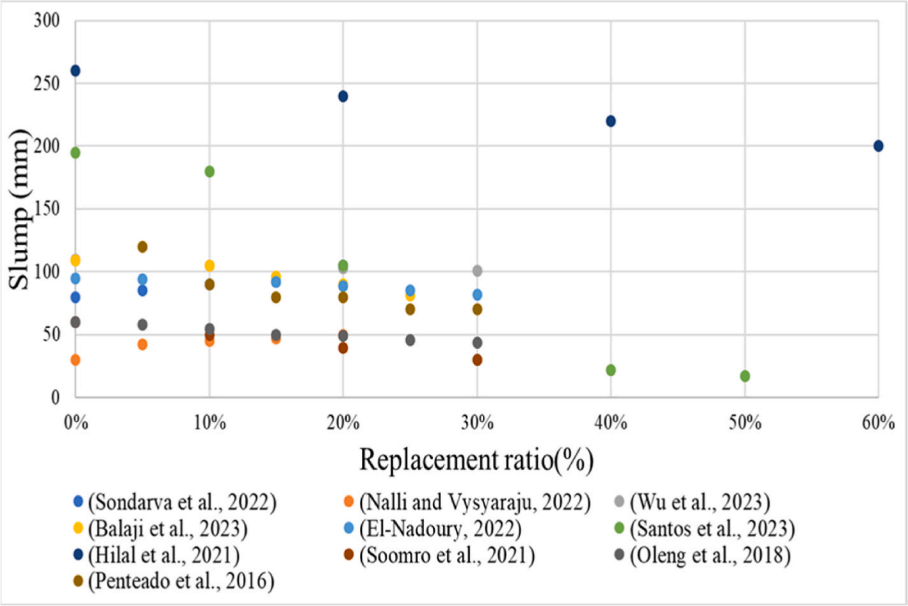


Fig. .21. The influence of CTP on the workability of different types of cement-based composite (Adapted from (Balaji et al., 2023; El-Nadoury, 2022; Hilal et al., 2021; Nalli and Vysyaraju, 2022; Oleng et al., 2018; Penteado et al., 2016a; Santos et al., 2023; Sondarva et al., 2022; Soomro et al., 2021; Wu et al., 2023)).

5. Setting time

In general, the water-binder ratio, fineness, mineral and chemical composition and other elements have an effect on the setting time of cement paste (El-Kattan et al., 2020; Khan et al., 2014; Xu et al., 2022b). As presented in Table 6, majority of researchers have noticed that the integration of CTP prolongs the setting time of cement. Pitarch. et al. (2021) stated that the initial setting time of the cement paste was slightly prolonged (up to 20 additional minutes) by replacing cement with CTP. This is mainly owing to the lower cement content compared to 100% OPC samples, which shortens the activation phase and causes a delay in setting (Ezziane et al., 2010). Nevertheless, the use of finer sized CTP gives different result due to the effects of fineness on the chemical reactivity. Researchers elsewhere, El-Kattan et al. (2020), found that setting times were reduced for mixes in which ultrafine CTP was used instead of cement. The large surface area results in mainly open pores being filled and the high pozzolanic activity of silicate rich CTP leads to the shorter setting times. In addition, a higher grain surface area provides more surface area for nucleation and hydration product development, increasing the reaction rate of the system (Oey et al., 2013). In general, it can be concluded that the utilize of CTP of different fineness influences the setting time of concrete.

Table 6
Impacts of CTP on setting time.

Reference	CTP content (%)	Median particle size	Effect
Awoyera et al. (2017a)	15, 25, 35,50	17.28 μm	Increased
(Pitarch. et al., 2021)	15,25,35, 50	14.01 μm	Increased
Awoyera et al. (2017b)	10,20,30	<53 μm	Increased
El-Kattan et al. (2020)	5	–	Decreased
Babatola and Arum (2020)	5,10,20	>45 μm	Increased
Mohit et al. (2023)	0, 20, 30	10 μm	Increased

6. Hardened properties

6.1. Dry density and compressive strength

Dry density has a significant effect on the compressive strength of concrete and is therefore one of the key properties of concrete. (Aslam et al., 2016; Shafigh et al., 2013). The incorporation of CTP in concrete resulted in a detraction in the hardened density of the concrete owing to the inferior particle density of CTP than cement. Hilal et al. (2020) found that the use of CTP with lower specific gravity value than cement produces concrete with lower dry density. A similar pattern has also been noticed by other researchers (Anand Kumar et al., 2016; Hilal et al., 2021).

In terms of compressive strength, researchers have found that the use of CTP leads to a decrease in the 28 days compressive strength of the cement based composite as the degree of substitution increases (AlArab et al., 2022; Lim et al., 2022; Pereira-de-Oliveira et al., 2012b; Pitarch et al., 2021b; Taher et al., 2023; Wu et al., 2023b; Xu et al., 2021). Nevertheless, the replacement of cement with up to 10% CTP resulted in a small decrease in compressive strength. The investigation showed that the compressive strength of the test specimens decreased by a maximum of 15 % during a period of 28 days compared to the control specimens (AlArab et al., 2022; Mansoori et al., 2021; Mas et al., 2016; Pereira-de-Oliveira et al., 2012a; Pitarch et al., 2021a; Taher et al., 2023). In general, the decrease in compressive strength observed could be attributed to the relatively lower or similar fineness of CTP compared to cement. Typically, lower levels of fineness in comparison to cement lead to a decrease in pozzolanic and filling capabilities. It is worth noting that a substantial decrease in the 28-day compressive strength was noticed when the substitution ratio surpassed 20% (Aswin et al., 2018; Penteado et al., 2016b; Pereira-de-Oliveira et al., 2012a). This significant reduction in compressive strength is mainly due to the prevailing dilution effect. However, the addition of up to 30% CTP to the mix resulted in a relatively small decrease in compressive strength at later stages of the curing process, especially at 90 and 365 days (Faldessai et al., 2023; Gautam et al., 2022a). Pitarch. et al. (2021) found a reduction in mortar strength of 35 % CTP of only 10% compared to the reference mortar after 365 days of curing. The observed phenomenon can be attributed to the fact that the CTP surface undergoes a gradual reaction with calcium hydroxide (CH) at later stages, resulting in the formation of a significant amount of calcium silicate hydrate (CSH) on the surface. This process leads to a strong bonding structure between the cement and the filler particles, which promotes the development of compressive strength in later stages (Ferrara et al., 2019; Ouyang et al., 2022a). Lasseuguette. et al. (2019) examined the effects of white and red CTP as a cement substitute on mortar. The result showed that the blended mortars for all mixes had slightly lower compressive strength than the OPC mortar, except for the 15% mortar, which was equivalent to the control up to 56 days and greater than 90 days (23.2 MPa versus 21.8 MPa). The blended cement had higher CSH concentrations up to 56 days, while the blended specimens had up to 12.5% CSH, compared to only 4% CSH in the normal OPC. The white ceramic was found to be more reactive relative the red ceramic. In the specimens with 15% white ceramic, 5% more CSH was absorbed than in the sample with 15% red ceramic. This could be due to the fact that white ceramics have a higher silica concentration than red ceramics, which means a higher potential reactivity. Pitarch. et al. (2021) claimed that the compressive strength of mortars did not alter considerably when OPC was partially replaced by CTP up to 25%. Another researcher Heidari et al. (2019) produced concrete utilizing CTP as a substitute for cement up to 15%. The result showed a sharp reduce in compressive strength at an early age, especially at 15% replacement. This is because at an early age, the CTP performs as a filler without the pozzolanic effect. However, at 28 days compressive strength results showed the mix with CTP exhibit strength close to the control specimens. Mohammadhosseini et al. (2019a) also observed similar trend in the performance of water cured mortar upon the integration of CTP as partial cement replacement.Recent research shows that thermal treatments may compensate the adverse effects of CTP on strength. Taher. et al. (2023b)conducted a study showing that heat treatment of CTP resulted in an increase in compressive strength compared with untreated CTP. The results show that the addition of up to 50% thermally treated CTP resulted in comparable strength to the control concrete.

On the contrary, alternative studies found that the presence of CTP with a certain degree of substitution has a positive influence because it increases reactivity and the ability to act as a micro filler. Previous studies have shown that the ideal ratio of cement to CTP is between 10 and 20%, resulting in a remarkable increase in compressive strength after 28 days, ranging from 5 to 22% (Aswin et al., 2018; Ebrahimi et al., 2023; Faldessai et al., 2023; Hilal et al., 2021; Li et al., 2020d; Mohit and Sharifi, 2019; Shanmugam et al., 2020; Sondarva et al., 2022; Taher et al., 2023). In another study, the use of nano-CTP as a cement replacement resulted in a remarkable increase in compressive strength of 40% after 28 days compared to the control group (Lim et al., 2018). Xu et al. (2021) reports that using CTP as a cement replacement below 45% improves compressive strength of UHPC and 25% CTP is the optimum amount as it produces specimen with highest strength value. This could be due to the fact that CTP with pozzolanic activity can react with CH to increase cement hydration and the formation of additional CSH gel (Heidari and Tavakoli, 2013; Irassar et al., 2014). Filling the pores with CSH gel densifies UHPC, and forming additional CSH gel reduces porosity and increases compressive strength (as shown in Fig. 23) (Oertel et al., 2014). However, use of up to 55% CTP reduces the UHPC strength. Excessive reduction in cement content deters the hydration process thus resulting in lesser CSH gel and calcium hydroxide for the occurrence of pozzolanic reaction. Mansoori et al. (2021) stated that the utilize of CTP as a cement substitute affected the compressive strength of self-compacting concrete. The outcomes revealed that the use of 10% and 20% CTP decreased the compressive strength by 7% and 19%, consequently. The 28-day compressive strength of the samples was more than 20 MPa, which makes them suitable for structural concrete. Fig. 22 shows the impacts of CTP on the compressive strength of different types of cement-based composite (see Fig. 24).

6.2. *Flexural strength*

. Previous studies have shown that the inclusion of CTP results in a decrease in the flexural strength of the cement-based composite at the 28-day curing as the degree of replacement increases (AlArab et al., 2022; Atkuri and Rao, 2021; Li et al., 2020a; Li et al., 2023b; Mansoori et al., 2021; Taher et al., 2023). Prior research has indicated that the incorporation of up to 10% CTP leads to a marginal reduction in flexural strength after 28 days, with the highest observed decline ranging from 5.8% to 17% (AlArab et al., 2022; Atkuri and Rao, 2021; Li et al., 2023b; Taher et al., 2023). However, the negative effect of CTP on strength gradually decreased with a long curing time of 56 days or longer (Atkuri and Rao, 2021; Li et al., 2023b). This phenomenon could be due to a secondary hydration reaction between CTP and calcium hydroxide ($Ca(OH)_2$) leading to the formation of additional calcium silicate-hydrate (CSH) gels. These gels effectively fill the pores and interfacial transition zone (ITZ), resulting in a denser matrix structure (Li et al., 2023b). On contrary, Multiple studies have demonstrated that incorporating 5%–35% of CTP as a substitute for cement notably enhances the 28 days flexural strength of cement-based composites (Balaji et al., 2023; Bhargav and Kansal, 2020; Ebrahimi et al., 2023; El-Nadoury, 2022;

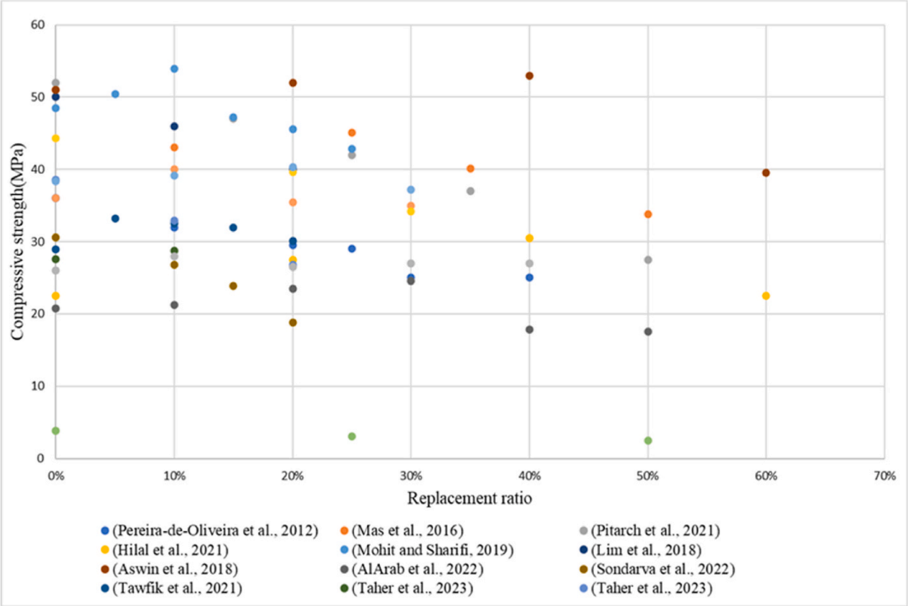


Fig. 22. The impacts of CTP on the compressive strength of different types of cement-based composite (Adapted from (AlArab et al., 2022; Aswin et al., 2018; Ebrahimi et al., 2023; Faldessai et al., 2023; Hilal et al., 2021; Lim et al., 2018; Mas et al., 2016; Mohit and Sharifi, 2019; Pereira-de-Oliveira et al., 2012a; Pitarch et al., 2021a; Sondarva et al., 2022; Taher et al., 2023; Tawfik et al., 2021; Wu et al., 2023b)).

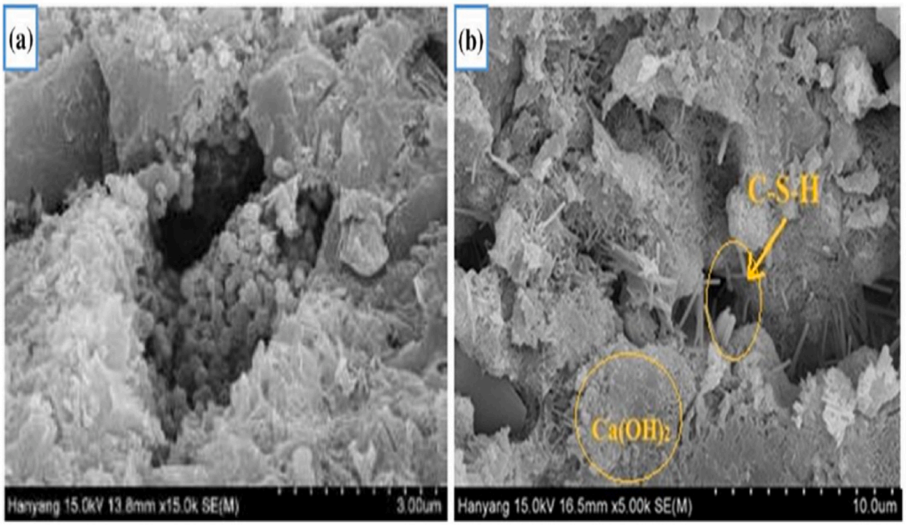


Fig. 23. SEM image of water-cured **a)** cement mortar and **b)** mortar with CTP (Adapted from (Mohammadhosseini et al., 2020b)).

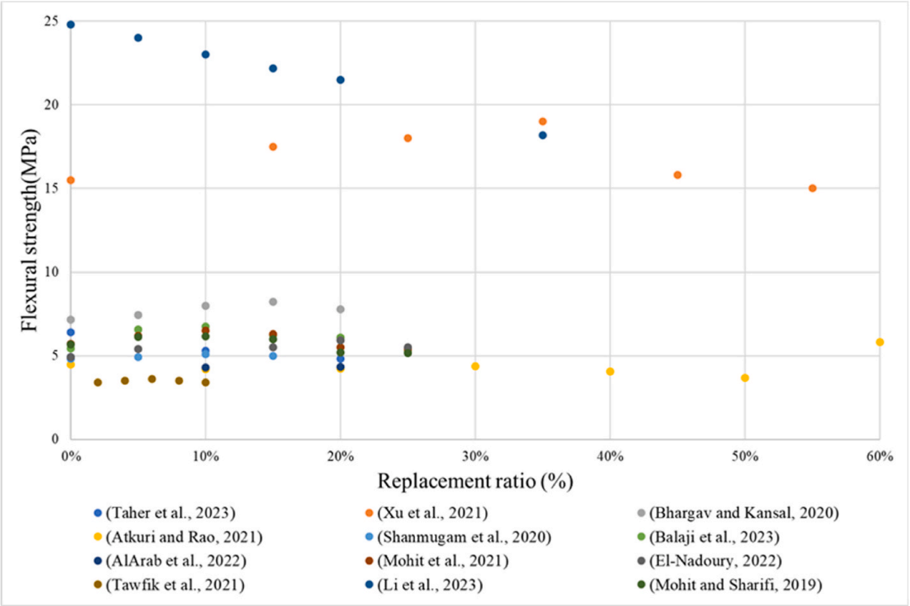


Fig. 24. The impact of CTP on the flexural strength of different types of cement-based composite (Adapted from (AlArab et al., 2022; Atkuri and Rao, 2021; Balaji et al., 2023; Bhargav and Kansal, 2020; El-Nadoury, 2022; Li et al., 2023b; Mohit et al., 2021; Mohit and Sharifi, 2019; Shanmugam et al., 2020; Taher et al., 2023; Tawfik et al., 2021; Xu et al., 2021)).

Ganesh et al., 2018; Manogna and Srilakshmi, 2015; Mohit et al., 2021; Mohit and Sharifi, 2019; Shanmugam et al., 2020; Tawfik et al., 2021; Xu et al., 2021).The observed increase in strength can be attributed to the pozzolanic reactivity of CTP. This contributed to the densification of the microstructure, which in turn increased the pliability of the specimen. (Irassar et al., 2014; Praseeda and Rao, 2021; Sharifi et al., 2020). In addition, CTP is regarded as a filler substance that has the capacity to partly occupy the empty spaces and/or openings between cement, leading to a physical enhancement in the density of granules (Tawfik et al., 2021).However, the previous research demonstrates that the compressive strength reduces when the substitution ratio goes beyond 35%. The prime contributor to this occurrence is the dilution effect, which is a well-established phenomenon. Xu et al. (2021) observed that ultra-high-performance concrete (UHPC) produced using CTP up to 35% replacement exhibited enhanced flexural strength relative to the control samples at 7 and 28 days of curing age. The same researcher noted that, the same mix demonstrated inferior strength in relative to control specimen at 3 days of curing age. Similar trend of low early strength was noted by Li et al. (2020a) who found that concrete produced using 10% CTP had lower strength than control samples at 7 days of curing age, which then exhibited enhanced flexural strength after being cured for 28 days.

The low early strength of concrete containing CTP is owing to incomplete pozzolanic reaction that is vital for the development of CSH gel which adds to the strength increment. The blending of suitable content of CTP at 6% (Tawfik et al., 2021), 10% (Ahmad and Alhayani, 2022; Li et al., 2020a; Mohit and Sharifi, 2019) and 35% (Xu et al., 2021) as partial cement substitute raises flexural strength of concrete. Tawfik. et al. (2021), who explored the impact of nano-CTP as a cement substitute on the flexural strength of concrete, reported that the utilize of nano sized particles in smaller percentage successfully increased concrete strength. The utilize of finer material would promote faster chemical reaction resulting in the development of a higher amount of CSH gel in shorter period of time as relative to the mix with larger sized pozzolanic ash. This variation in the result is due to the diverse oxide composition and uniqueness of the method applied in processing the pozzolanic ash that influences the particle size of the material. Although using large amounts of CTP would contribute to a more sustainable construction material, the concrete would suffer strength decline. Fig. 26 shows the impact of CTP on the flexural strength of different types of cement-based composite.

6.3. Splitting tensile strength

The splitting tensile strength of concrete not only provides information about the incremental cracking patterns under tensile stress but also serves as an indirect way to assess the load under which cracking occurs in the material (Awoyera et al., 2018; Fapohunda et al., 2017). Recent research has shown that the use of CTP leads to a reduction in the splitting tensile strength of cement-based composites over a period of 28 days (AlArab et al., 2022; Atkuri and Rao, 2021; Taher et al., 2023).The magnitude of this loss is directly proportional to the degree of substitution. However, substitution of cement with a maximum of 10% CTP resulted in only a small reduction (13%) in the splitting tensile strength (AlArab et al., 2022; Atkuri and Rao, 2021; Taher et al., 2023). Similar to the compressive strength, the observed reduction in tensile strength can be attributed to the relatively lower or comparable fineness of CTP compared to cement. It is worth noting that there was a significant reduction in tensile splitting strength after 28 days when the substitution ratio exceeded 30% (AlArab et al., 2022; Atkuri and Rao, 2021; Taher et al., 2023). The main cause of the significant reduction in splitting tensile strength can be attributed to the predominant dilution effect. Nevertheless, the incorporation of a maximum of 30% CTP into the mix resulted in relatively lower reduction in the splitting tensile strength during the later stages of the curing process, particularly at the 56 and 90 day of curing (AlArab et al., 2022; Atkuri and Rao, 2021). Mohammadhosseini et al. (2020b) stated that the inclusion of CTP improves the splitting tensile strength of mortars upon exposure to longer curing time. Blended cement-CTP mortar exhibited slightly lower early strength at about 4% in comparison to plain concrete before undergoing strength increment to about 15% greater than the latter at 90 days curing. The lessening in cement content due to use of CTP that is responsible for hydration process lessen the quantity of binding gel. The beneficial effect of pozzolanic reaction from the CTP transforms the microstructure of mortar to be denser and higher strength than control specimen. On the other hand,. Previous studies have shown that using CTP as a cement replacement increase splitting tensile strength on the order of 5%–25%, with improvements ranging from 4% to 18% (Bheel et al., 2019; Daniel and Raju, 2018; El-Nadoury, 2022; Lim et al., 2022; Oleng et al., 2018; Shanmugam et al., 2020; Sharma et al., 2021; Sondarva et al., 2022; Tawfik et al., 2021). The observed increase in splitting tensile strength can be attributed to two key factors: the pozzolanic process within the cement matrix and the filling effect created by the tiny particles in the concrete matrix (Awoyera et al., 2017a). Tawfik. et al. (2021) claimed that the utilization of higher fineness CTP of nano-size raises the splitting tensile strength of concrete to more than the control sample. A proportion of 6% nano-CTP as cement replacement caused the largest rise in the splitting tensile strength. Improvement in the processing methods for the production of CTP with high pozzolanic reaction that can enable the usage of this waste in high volume for concrete production with enhanced strength, remains to be explored. Fig. 25 shows the impact of CTP on the Splitting tensile strength of different types of cement-based composite.

7. Durability

7.1. Resistance to sulphate attack

Sulphate, if present in the soil or seawater, can attack OPC concrete exposed to it. Ettringite (calcium aluminium sulphate hydroxide) forms when calcium hydroxide combines with a sulphate solution in concrete. This sulphate solution then reacts with calcium sulphate to form calcium sulphate ($CaSO_4$). Ettringite formation results in expansion (El-Hachem et al., 2012a, b; Nayana and Rakesh, 2018). Samadi et al. (2020) found that the use of 40% of CTP in mortar specimens, submerged in 5% Na_2SO_4 resulted in a decline in mortar compressive strength loss. As can be noticed in Fig. 26a, the residual strength of specimens 0% and 40% CTP had decreased by 41.1% and 16.8%, respectively, after 18 months of immersion. Mohammadhosseini et al. (2020b) noted that after 3 months in the solution, the data showed that the OPC mortar had lost

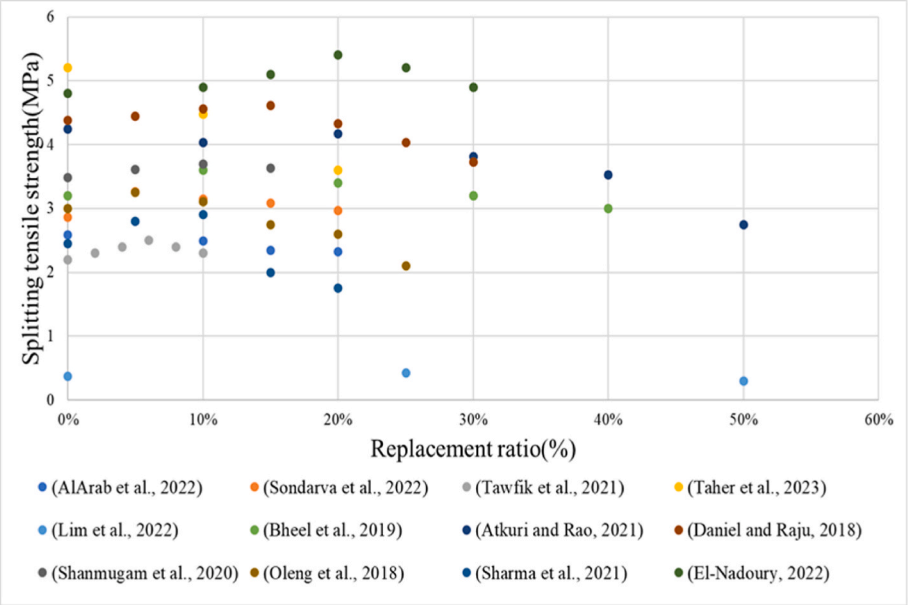


Fig. 25. The impact of CTP on the Splitting tensile strength of different types of cement-based composite (Adapted from (AlArab et al., 2022; Atkuri and Rao, 2021; Bheel et al., 2019; Daniel and Raju, 2018; El-Nadoury, 2022; Li et al., 2023b; Lim et al., 2022; Oleng et al., 2018; Shanmugam et al., 2020; Sharma et al., 2021; Sondarva et al., 2022; Taher et al., 2023; Tawfik et al., 2021)).

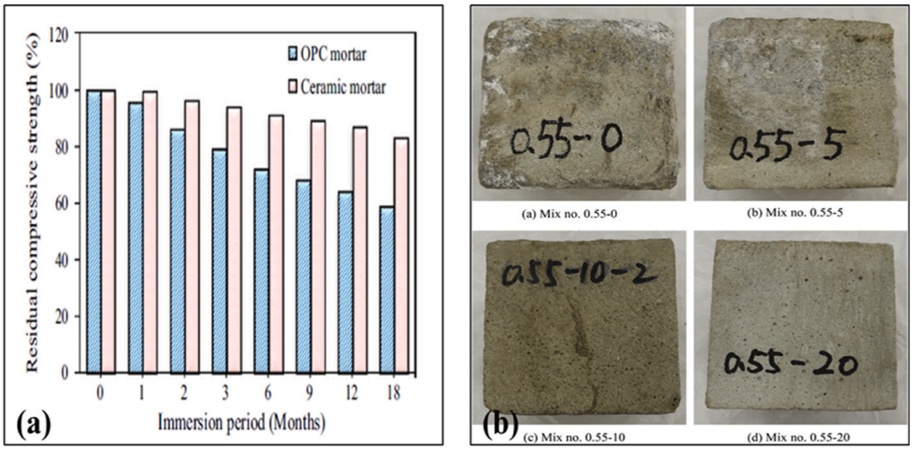


Fig. 26. Impact of CTP on mortar when exposed to sodium sulphate a) compressive strength (Adapted from (Mohammadhosseini et al., 2020b) b) physical properties (Li et al., 2020c)).

0.7% of its mass, while the CTP mortar had gained 1.7%. Li et al. (2020c) found that when 5% and 10% CTP was used in mortars, the mortars were less prone to spalling and less cracks developed on the surfaces, while when 20% CTP was utilized, no spalling occurred, and no cracks developed (as shown in Fig. 26b). The integration of CTP that consumes the vulnerable calcium hydroxide to produce additional CSH gel contributes to denser internal structure of concrete with better resistance towards sulphate attack. The formation of CSH gel reduces the porosity of cement-based composites and increases their sulphate resistance by densifying the pores structure (Praseeda and Rao, 2022). The effectiveness of CTP of various fineness on the resistance of concrete against sulphate attack should be explored. The sulphate resistance of high-performance concretes containing CTP as partial cement replacement remains to be researched.

7.2. Resistance to acid attack

Resistance to acid attack is critical for exterior applications of concrete. Mohit et al. (2021) explored the effects of CTP as a cement substitute on mortar exposed to hydrochloric acid attack. 56 days after acid curing, the mass loss of the control sample was 8.64%, while the mass loss of concrete with 5, 10, 15, 20, and 25% CTP was 7.11%, 7.74%, 7.92%, 8.37%, and 9%, respectively. Meanwhile, the compressive strength of the samples mixes with 5, 10, 15, 20 and 25% CTP decreased

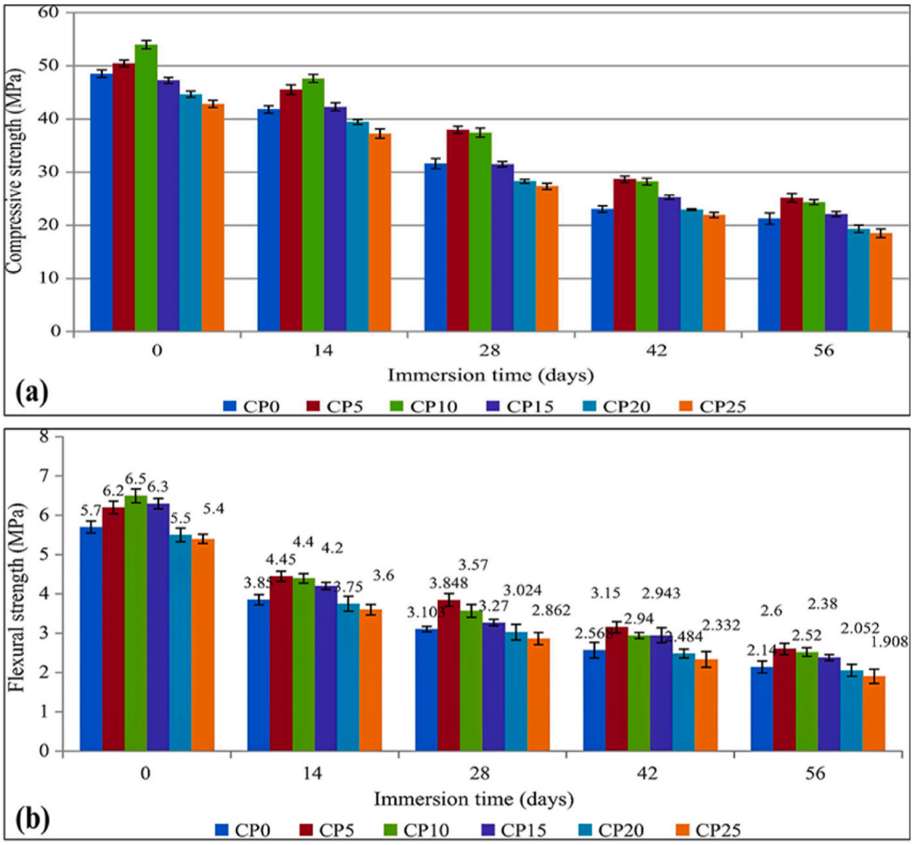


Fig. 27. The impact of CTP on the acid resistance of mortar,a) Compressive strength b) Flexural strength (Adapted from (Mohit et al., 2021)).

by 50.1%, 54.8%, 53.2%, 56.7% and 56.8%, respectively, while it decreased by 56.2% for the control specimen. The concrete with 5% CTP showed the least strength loss over time, while the mixes with 25% CTP showed the greatest strength loss after exposure to acid attack as shown in Fig. 27. The concretes formed using CTP exceeding optimum amount display poor resistance towards acid attack due to lesser CSH gel formed because of the lower cement content, which also affects the pozzolanic reaction. A similar findings was observed by Sharifi et al. (2020), who found that the utilize of CTP as a cementing material increased the resistance of the specimens to sulfuric acid compared to the control specimens. Concrete containing CTP has the potential to resist acid attack by densifying the structure of the concrete through a pozzolanic reaction, caused a slowing of the transfer of the acid solution (El-Kattan et al., 2020; Li et al., 2020b; Mohammadhosseini et al., 2020b; Sharifi et al., 2020). Acid resistance of binary, ternary or quaternary blended cement concrete with CTP as partial cement replacement remains to be explored. Further research remains to be conducted to determine approaches to produce high volume CTP blended cement mix which is able to exhibit superior resistance against acid attack.

7.3. Chloride ion penetration

Chloride is primarily responsible for accelerating the corrosion of reinforcing steel. Chloride penetration into concrete is one of the most detrimental processes influencing the long-term durability and safety of concrete structures (Shi et al., 2012; Tahri et al., 2021; Wang et al., 2013). CTP is known to change the pore structure of pastes and the transition zone (ITZ) between pastes and aggregates, which affects the pore structure of concrete. El-Dieb and Kanaan (2018) investigated the effects of chloride ion penetration into concrete containing 10, 20, 30, and 40% CTP. At 28 days of age, the CTP replacements of 10, 20, 30, and 40% had corresponding chloride penetration values of 3899, 2517, 864, and 590 coulombs, respectively. This could be due to pozzolanic effect of CTP that also provides densification of the microstructure and pore structure refinement. Chen et al. (2022) investigated the impacts of CTP as a cement substitute on the chloride ion penetration of recycled aggregate concrete (RAC). They found that the introduction of CTP reduces the total charge transferred through the RAC. For example, when 10% CTP was added, the total charge transferred by the RAC decreased by 27.3%. However, as the percentage of CTP increased, the total charge of RAC also increased (as illustrated in Fig. 28b). Mohammadhosseini et al. (2019a) studied the impacts of CTP as a cement substitute on mortar. At 18 months of age, the mass of mortar samples enhanced by 3.8% for OPC and by 2% for the CTP mortar mixes (as shown in Fig. 28a). The mortar containing CTP had an average penetration depth of 5 mm, while the control mortar had a penetration depth of 15 mm. The lower penetration of chloride ions in concrete with CTP is due to less permeable pores than in concrete without ceramic waste (Kannan et al., 2017).

7.4. Other properties

Capillary sorptivity is the potential of a porous substance to absorb liquid water through open and connected capillary pores (Esen and Doğan, 2017). Li et al. (2020b) stated that the utilize of CTP up to 40% as cement substitute reduces the sorptivity of mortar. The decrasing in water absorption capacity can be up to 60% when the percentage of CTP is 40%. Another researcher elsewhere Chen et al. (2022), using 10% substitute of CTP, observed that the initial and secondary water absorption of recycled aggregate concrete was lessened considerably. This can be explained by the fact that the CTP has a smaller grain size than cement, leading to a micro filler effect. A more homogeneous mortar matrix is formed through pozzolanic reaction resulting from the integration of CTP (Sánchez de Rojas et al., 2018). Formation of larger amount of CSH gel upon the use of suitable combination of CTP content contributes positively towards more compact interior structure of the concrete.

Drying shrinkage of concrete can significantly affect the spread of cracking, effective tensile strength, loss of prestress, warping, and other properties of the concrete structure (ACI, 2009). El-Dieb and Kanaan (2018) explored the effects of CTP as a cement substitute on drying shrinkage. It was found that the tendency for drying shrinkage decreased for all mixes when the CTP replacement was increased. A considerable reduction in drying shrinkage was observed when the replacement was greater than 20% for all grades. Drying shrinkage decreased by 29%–60% when CTP was used in amounts greater than 20% relative to the control blend. Blends at 50 MPa displayed a 28–53% reduction in drying shrinkage when more than 20% CTP was used. For the 75 MPa mixes, drying shrinkage was reduced by 25–27%. Kanaan and EL-Dieb (2016) found that the drying shrinkage values decreased by 5%–60% when CTP was used in amounts up to 40% compared to the control mix. When high performance concrete mixes were used, drying shrinkage was reduced by 12–27%. Mohammadhosseini et al. (2019b) noted that the drying shrinkage of mortar incorporating CTP was much inferior relative that of control mortar. On average, the drying shrinkage of OPC and CTP mortar is $993 - 10^{-6}$ and 837×10^{-6} macrostrain after 90 days of ageing, respectively. The drying shrinkage of the mortar was substantially declined by the addition of CTP, which reduced the free water content in

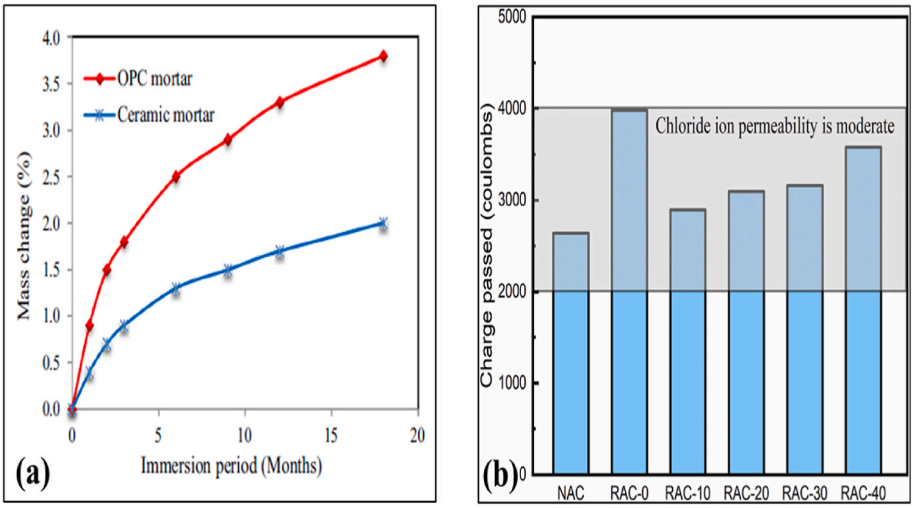


Fig. 28. The effect of CTP chloride penetration a) mortar (Mohammadhosseini et al., 2019a)b)recycled aggregate concrete (Adapted from (Chen et al., 2022)).

the capillary pores. According to Steiner et al. (2015), there are two main causes of the reduction in drying shrinkage: i) CTP's pozzolanic action, which favours a delayed reaction in which pozzolanic ash absorb large quantities of water in their surfaces and discharge it to the environment during hydration of cement, thereby decreasing the capillary pressure between the particles, and ii) the influence of cement dilution. Another researcher elsewhere, Mansoori et al. (2021), also reported a lower drying shrinkage of fibre reinforced self-compacting concrete with CTP and microsilica as cement replacements. Further investigation into the drying shrinkage of CTP blended cement based fibre reinforced concrete, high strength concrete and ultra high performance concrete will also be interesting.

Mohit and Sharifi (2019) examined the impacts of CTP on the fire performance of concrete. Results demonstrated that the utilization of CTP as a cement substitute at 5%, 10%, and 15% enhanced compressive and flexural strength up to 400 °C. At 600 and 800 °C, the greatest compressive and flexural strengths were observed in the blends with 20% and 25%, respectively (as shown in Fig. 29) Furthermore, cracking on the surface of concrete containing CTP was found to be significantly lower at temperatures between 600 and 800 °C, especially for mixes containing 25% and 20% CTP. Hilal et al. (2021) reported that at temperatures up to 800 °C, the peak value of the compressive strength of 36 MPa was obtained for a sample containing 20% CTP. AlArab et al. (2020) found that the mass loss for the pastes with CTP added was about 15%, while it was 25% for the control sample. The utilize of CTP enhances the fire resistance of concrete owing to the development of CSH benefitting from pozzolanic effect (Lasseuguette et al., 2019). Generally, incorporation of pozzolanic ash of right amount as partial cement substitute increases the fire resistance of concrete. Nevertheless, the effectiveness of CTP of various fineness and contents towards fire resistance of modern cement-based concretes remain to be explored.

7.5. Specific conclusions

From the preceding remarks the following conclusions can be derived:

1. CTA particles have a greater water absorption capacity compared to natural aggregates, resulting in an increased water requirement. Therefore, it is advisable to formulate cement-based composites using CTA blends with the aim of obtaining constant slump, rather than designing them based on a fixed water-binder ratio.
2. The use of CTA aggregates (coarse or fine) generally reduces the workability of cement-based composites. This is mainly due to the high-water absorption of CTA compared to natural aggregates.
3. When coarse aggregate is replaced by CTA aggregate, the mechanical properties of concrete mainly increase with an increase of CTA content up to 30% and decrease with an increase of replacement.
4. When fine aggregate is replaced by CTA aggregate, the mechanical properties of concrete mainly increase with an increase of CTA content up to 60% and decrease with an increase of replacement.
5. CTP can serve as a partial substitute for cement because its total composition of silicates, aluminates, and iron oxide is generally above the 75% limit specified in ASTM 618.
6. The addition of up to 20% CTP improves the mechanical properties of cement-based composites, including compressive strength, flexural strength and split tensile strength.
7. The use of CTP as a substitute for cement, at a maximum replacement level of 20%, resulted in enhanced durability of cement-based composites. The cementitious composite, which consisted of up to 20% CTP, demonstrated reduced drying shrinkage, permeability, chloride ion penetration, and carbonation, while exhibiting enhanced resistance to sulphate attack.

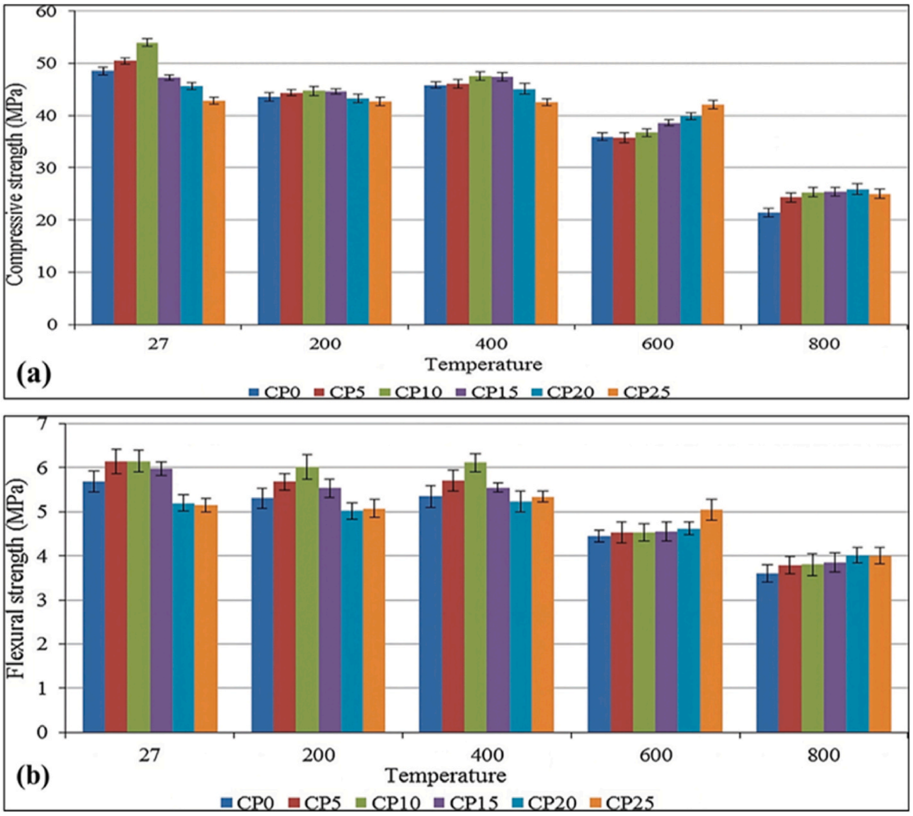


Fig. 29. Impact of CTP on the of mortar at elevated temperature (Adapted from (Mohit and Sharifi, 2019)), a) Compressive strength, b) Flexural strength.

8. Recommendations for future research

This research has shown that there are several gaps in the existing literature, and it is suggested that future investigations into this field concentrate on the following areas:

1. A numerical assessment of the financial and ecofriendly profits should be conducted against the gain or loss of compressive strength, flexural strength, splitting tensile strength and modulus of elasticity when ceramic waste of various percentages is used as mixing ingredient in concrete.
2. The effectiveness of employing CTP produced from combination of mechanical activation, thermal activation and chemical activation towards properties of concrete should be explored.
3. An experimental work in terms of structural analysis of concrete beams or slabs produced using high volume CTP as cement replacement.
4. Further research should be carried out to investigate the durability performance of concrete consisting CTW as cement and aggregate replacement upon exposure to different types of acids under diverse conditions, and tropical seawater.
5. Further research should be conducted to examine the durability performance of different sizes of CTP as a cement and aggregate substitute on the sulphate and acid resistance of different types of concrete, such as normal, high strength, ultra-high performance concrete mixes, self-compacting concrete and fibre reinforced concrete.
6. In order to expand the application of this material in modern concrete, supplementary experimental work should be conducted to determine the effect of ceramic tile waste on the mechanical and durability performance of modern cement-based concrete namely high workability concrete, lightweight aggregate concrete, pervious concrete, fibre reinforced concrete and foamed concrete.
7. In view of natural aggregate resources sustainability and circular economy approach, investigation on the formation of fine and coarse aggregate using CTW which is suitable for concrete production is another area remain to be explored.

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

The authors are unable or have chosen not to specify which data has been used.

Acknowledgements

The authors would like to thank Universiti Malaysia Pahang Al-Sultan Abdullah for supporting the study through the internal research grant RDU223306.

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