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Factors affecting the CO_2 emissions, cost efficiency and eco-strength efficiency of concrete containing rice husk ash: A database study

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Abstract

The agriculture industry has grown dramatically by about three times over the last 50 years due to the rapid population growth, improvements in green production technology and agricultural land development. Rice is the second most-consumed agricultural product globally. The rice husk ash (RHA), attained by burning the husk that is removed in the process of rice production, possesses high pozzolanic activity and therefore is a promising supplementary cementitious material. Despite the numerous studies on the successful incorporation of RHA in concrete in the literature, a comprehensive assessment on the sustainability aspects of these practices has not yet been solely and exclusively addressed. The paper reports findings from the analysis of a large database on the RHA incorporation in concrete. Principal sustainability components such as CO_2 emissions, cost efficiency and eco-strength efficiency are described. The database, comprising over 1000 data points has been utilized to assess the key factors that have significant influences on the mechanical properties of concrete comprising RHA using the established set of criteria. Independent determination of the boundary conditions played a vital role in the sustainability assessment. The results showed that the use of RHA along with the other pozzolanic materials can yield a 25% diminution in the CO_2 emissions generated during the concrete production in conjunction with a 65% rise in the cost efficiency of such practices. The findings reported in this study demonstrate improved sustainability for construction practice and highlight greener waste management routes that can be established for RHA.

Keywords

Rice husk ash, waste utilisation, database, CO_2 emissions and cost efficiency, cleaner waste management alternative route, cement.

1. Introduction

The dramatic increase of environmental pollution and its associated adverse effects on health is threatening the entire planet unprecedentedly. One of the major contributors for this is the unlimited generation of raw materials from the continual increase in demand for food production particularly in developed countries (Bhuvaneshwari et al., 2019). It is widely known that most of the main agricultural production was cultivated for thousands of years in what is now entitled ‘developing’ countries’ (de Candolle, 1886; Vavilov, 1926; Harlan, 1975; Simmonds, 1976; Fowler et al., 2001). Throughout history, the utmost focus of genetic diversity has correspondingly been constituted in the developing countries (Vavilov, 1926; Zeven and Zhukovsky, 1975; Pretty et al., 2003). Waste generation, substantially grows due to the dramatic rise in the consumption of raw material and is expected to reach 3.4 billion tons by 2050 (Kaza et al., 2018). Some of the most common disposal methods further contribute to environmental damage. For instance, Sathiparan and De Zoysa, (2018) stated that, open dumping and burning, the two frequently utilized methods for waste disposal, have substantial adverse effects on human health and environment.

The agriculture industry, for instance, has dramatically grown by about three times over the last 50 years due to the growing population, improvements in green production technology and agricultural land development (Bhuvaneshwari et al., 2019; FAO, 2017; FAO, 2019). As defined by Ramírez-García et al.

2019, agricultural waste, undesirably generated by agricultural activities, significantly contributed to waste generation primarily as a result of the increase in agro-based products. Although the environmental pollution and its associated health hazards caused by the agricultural wastes are a key global challenge, the inadequacies of waste disposal methods is one of the most devastating factors influencing the environmental deprivation (Ramírez-García et al., 2019). Incineration, for instance, is leading a substantial increase in the production of greenhouse gas emissions (Bhuvaneshwari et al., 2019). It is also documented in Sabiiti (2011) that burning agricultural waste is a conventional method particularly in under-developed nations. This approach is one of the biggest contributors to environmental contamination. Ezcurra et al. (2001) reported that, gaseous pollutants, in particular carbon monoxide, nitrous oxide, nitrogen dioxide and particles such as smoke carbon are liberated to the environment because of agricultural waste burning. These pollutants significantly contribute to acid deposition (Lacaux et al., 1992) as a result of ozone and nitric acid formation (Hegg et al., 1987), and hence endangering human and ecological health (Alston et al., 2014). Dumping, on the other hand, often adversely affects the soil properties mainly from the ingress of the methane gas in the land. Treatment methods or alternatively utilizing the wastes as fertilizer or animal food are often not reported to be environmentally friendly due to heavy chemicals used for this process that both pollute the environment and negatively affect the ecosystem (Vadiveloo et al., 2009). It must be emphasized that the potency of agricultural waste is a function of the quantity produced as well as the disposal methods utilized.

Rice, one of the most produced agricultural products, is the second most-consumed food item globally (Fernandes et al., 2016). It is an important staple food that provides half of the nutrients with a yearly production of 742 million tons (FAO, 2015). On the average, paddy comprises 72% rice, 5-8% of bran, and 20-22% of husk (Li et al., 2016; Muthadhi and Kothandaraman, 2010). The husk is removed in the process of the production of rice. Production of rice produces two types of husks. Bran surrounds the rice and has high nutritional properties. Glume (outer husk of rice) has a stiff structure and low nutritional properties. Glume comprises a high volume of amorphous silica and carbon content with low density and high volume (Yuzer et al., 2013). As Della et al. (2002) stated that cellulose, lignin, and inorganic compounds are the main ingredients of glume. It is reported in the literature that the inorganic portion contains, on average, 95% amorphous hydrated silica by weight. Although this is a cost-effective material, high silica content discourages recycling of rice husks by the rice production industry. Rice husks are also not suitable for animal feed due to the high silica content that results in the low nutritional value and potential to cause serious health problems due to accumulation within an animal’s body (Zerbino et al., 2011).

Maiti et al. (2016) demonstrated that the rice husk char attained through the rice husk gasification system could be used as a biomass energy source. It is extensively documented in Rigon et al. (2021) that rice husk is commonly used in thermal power stations which results in the formation of rice husk ash (RHA). Rice husk, substantially available in various developing countries, is used for the bioenergy production (Pode et al., 2015; Pode, 2016). It is also essentially reported in Rigon et al. (2021) that Brazil alone generates ~3.3

million tonne rice husk annually. Despite the fact that only a mere amount of this husk is currently used for the energy production in Brazil, it should be emphasised that the rice husk ash generation reaches up to 495.000 t annually. The biomass energy by means of gasification or thermally generated electricity is currently becoming a more common practice particularly in Asian countries. It should be emphasised that the several Asian countries such as India, China, Thailand, Cambodia, Malaysia, Indonesia, Philippines have already implemented rice husk gasification technology for power generation (Pode et al., 2015; Shackley et al., 2012; Lim et al., 2012). Biomass gasifiers are also recently used in rice mills in Cambodia to produce power for machine operations and office appliances (Pode et al., 2015; Shackley et al., 2012). Teixeira et al. (2016) also stresses the fact that essentially increasing amounts of fly ash is also being produced through the biomass combustion over the last years (Teixeira et al., 2016; Tarelho et al., 2012). Application of rice husk has also been addressed across a diverse range of applications in the literature. These include the utilization of rice husk in energy storage/capacitors, production of silica gels, silicon chips, manufacture of lightweight construction materials and protection, fertilizer, and to synthesis of activated carbon and silica. Rice husk ash (RHA), produced as from burning rice husk, is approximately 20% of the weight of the rice. However, the byproduct attained following the biomass operation is often disposed of in rivers or landfill which cause substantial soil contamination and water pollution (Liu et al., 2012).

It is widely reported in the literature that the RHA comprises primarily silicon dioxide (SiO_2) and smaller amounts of carbon (C), potassium oxide (K_2O), phosphoric oxide (P_2O_5) as well as calcium oxide (CaO). Magnesium (Mg), iron (Fe), and sodium (Na) could be present as an impurity (Rigon et al., 2021;

Venkatanarayanan and Rangaraju, 2013). The most commonly implemented methods of obtaining RHA comprise either uncontrolled burning or controlled combustion. The controlled combustion could be performed using the moving grate incinerators or bubbling fluidized bed reactors (Armesto et al., 2002; Fernandes et al., 2016; Ferraro et al., 2010). It must be emphasised that the chemical composition and structure of RHA is significantly affected by these procedures and more specifically by the temperature and the duration of these processes. (Ferro et al., 2007; Ferro, 2009; Rigon et al., 2021; Rafiee et al., 2012). Chandrasekhar et al. (2006) stated that surface melting takes place prior to the oxidation of carbon during rapid heating of the rice husk and this further results high carbon content of the ash and exhibits slightly darker colours as a result of the partial combustion (Isberto et al., 2019; Yang et al., 2016). Oxidation of carbon prior to the melting of silica is enabled when performing controlled combustion with lowered heating rate and therefore, the lower carbon content of ash and consequently gray or pinkish-white colour of RHA is obtained (Isbero et al., 2019; Anantha et al., 2016; Isberto et al., 2019; Chandrasekhar et al., 2006).

It must be emphasised that the complete combustion of RHA provides improved pozzolanic activity as a result of the improved reactivity, higher surface area as well as the formation of the amorphous structure of the ash (Rigon et al., 2021; Isberto et al., 2019; Cordeiro et al., 2009; Moraes et al., 2010). This pozzolanic character of RHA, which is significantly affected by the burning conditions, is essentially important when used as a binder substitute in cement and concrete. It is well documented in the literature that rice husk ash, obtained through the fluidized bed combustion process, possess high pozzolanicity and hence can react with calcium hydroxide and generate additional formations of calcium-silicate-hydrate (C-S-H) gels. The formation of C-S-H gels densify the cement matrix and enables improved durability and therefore is a promising supplementary cementitious material to be used in mortar and concrete making (De Sensale, 2010; Metha & Monteiro, 2014; Rigon et al., 2021).

It is also reported in Xu et al. (2012) that RHA has a porous microstructure, high specific surface area as well as high amorphous nano-silica content. Prasara and Gheewala, (2017), de Sensale et al. (2008) and James and Rao (1986) also stresses the fact that the chemical composition of RHA, more specifically the carbon content of the by-product, essentially depends on the combustion conditions. When calcined at temperatures greater than 700°C, crystalline silica alone is formed that can be utilised in the steel and ceramic industries only (Malhotra and Mehta, 1996). Conversely, when crystalline silica is subjected to air, it can be dangerous to human exposure as it often causes silicosis. Thus, the lower burning temperatures, particularly below 700°C, of RHA are recommended to produce amorphous silica that is suitable as a supplementary cementitious material (SCM) in construction materials as well as a filler material in rubber or paint industry (Prasara and Gheewala, 2017; He et al., 2017). The optimal combustion temperature is reported to be between 500–700°C for the attainment of the highest amorphous silica content (Msinjili et al., 2017; Nair et al., 2008; Rêgo et al., 2015; Xu et al., 2016). Using temperatures below 500°C led to an uncontrolled burning that does not properly convert the husk to ash due to the insufficient combustion, and consequently a substantial amount of unburnt carbon remained in the resulting ash. Carbon content above 30% is expected to have a negative impact on the pozzolanic activity of RHA (Cook, 1986). For instance, it is widely reported in Venkatanarayanan and Rangaraju (2013) and Corderio et al., (2009) that uncontrolled burning process results in a high-carbon content in the composition of RHA which could negatively affect the pozzolanic activity as well as the rheology of mortar and concrete. The correlation between the chemical composition of RHA and the burning conditions such as the temperature and the duration are also widely reported in Ferraro et al., (2010), Rafiee (2012), De Sensale (2010), James and Rao (1986). Rigon et al., (2021) also emphasized that fact that fluidized bed method, enables uniform burning of biomass, and grate furnace combustion takes place along a temperature gradient. It is reported in the study that these processes have eminent influences on the characteristics of RHA. The RHA obtained through the controlled combustion often comprises greater reactive silica minerals compared to that of the uncontrolled combustion or the open-field burning. Silica obtained by means of this process also is in non-crystalline form, which is essential for the pozzolanic reaction. This form of silica can then reach with calcium hydroxide in the presence of moisture to produce calcium-silica-hydrate gels through the pozzolanic reaction.

It is comprehensively documented in the literature that incorporation of RHA provides significant improvement on the mechanical properties and durability characteristics of concrete (Madandoust et al., 2011; Ezcurra et al., 2001; Yuzer et al., 2013). The considerable enhancements on the compressive and flexural strength, reduction in permeability, enrichment in workability, and reduction in efflorescence due to reduced calcium hydroxide are commonly reported by researchers as a consequence of the incorporation of RHA in cement based materials (Mehta and Monteiro, 2014). It is previously indicated in the paper that the rice husk ash could be obtained through controlled or uncontrolled burning processes. As abovementioned, the controlled burning is more influential in attaining high pozzolanic activity of RHA, however uncontrolled burning is nevertheless reported to be a practice (Narra, 2011). It is also widely reported in the literature that the CO_2 emissions from burning are affected by a range of diverse conditions. These include the moisture content and chemical composition of rice husk, as well as the burning method and the duration and extent of burning (Arai et al., 2015). The studies meticulously sourced from the literature for the construction of the database often did not contain sufficient information regarding the burning process of the RHA. This feature, although critical, could not be considered herein due to the aforementioned inadequacies regarding the burning process of RHA.

It is reported in Qing-ge et al. (2004) that the utilisation of RHA as a cement substitute yielded a rise in the compressive strength of concrete. This feature further caused a great reduction in the average pore radius of the concrete, and decreased the amount of $Ca(OH)_2$ within the matrix. Zhang et al. (1996) also reported that the RHA, a high pozzolanicity material, enhanced the interfacial transition zone (ITZ) amongst the cement matrix as well as the aggregate in concrete. Yu et al. (1999) reported that in addition to the physical and mechanical properties, the durability could also be enhanced for RHA blended concrete due to formation of calcium-silicate-hydrate (CSH) gel and less portlandite, $Ca(OH)_2$. Saraswathy and Song (2007) further reported that incorporating RHA up to a substitution level of 30% decreased the permeability and hence the chloride penetration which considerably enhanced the corrosion resistance and strength of concrete.

Safiuddin et al. (2010) also demonstrated that optimal strength of concrete was attained when 15% RHA was added to the existing mixture in concrete. 5% RHA with respect to the total volume of binder, was reported to enhance mechanical properties of concrete when utilised as a cement substitute. Cordiero et al. (2009) investigated the incorporation of ultra-fine RHA (particle size of 3 µm). The study showed that the utilisation of 20% RHA as a cement substitute resulted in an enhancement of mechanical properties and durability. Rego et al. (2015) also reported that residual RHA was an appropriate supplement for cement even with low amorphous silica content. Chatveera and Lertwattanaruk (2011) utilized RHA with a fine particle size typically smaller than 12 µm where the cement substitution level was up to 20%. Enhanced strength and durability of concrete were attained in the study. Chopra et al. (2015) also documented that the use of RHA, up to 20% as cement substitute, increased the strength and durability in self-compacted concrete. Black RHA with a particle size of 12 µm was also reported to attain high strength concrete, particularly at 5% substitution (Mahmud, 2010). Sulfate, progressively attacks concrete and changes its internal microstructure, having a direct influence on engineering properties and processes such as swelling, spalling, and cracking (Marchand, et al., 2010). Bolla et al. (2015) stated that the RHA significantly improved the concrete durability in particular the resistance of concrete to sulphate attack. Bahri et al. (2018) also used black and grey RHA as a substitution of cement (20% by weight). It is shown in the study that the grey RHA enhanced the compressive strength by 30% due to the lower carbon content of the ash whereas, the black RHA lower the compressive strength by 30% compared to the control specimen.

The social aspects of the RHA utilization in concrete is rarely addressed in the literature (Prasara and Gheewala, 2017). Shacklet et al., (2012) investigated the greenhouse gas emission reduction, cost reductions and employment creation for rice husk ash applications using environmental, economic and social indicators and suggested that the ash could be used to substitute the charcoal as a sustainable option. Shacklet et al., (2012) also stresses the fact that a further research regarding the agronomic benefits of rice husk char on the health and ecological hazards resulting from char generation, storage and mobilization is required. Later in 2020, Jittin et al., (2020) also emphasized the social and environmental aspects of the open field burning of rice husk that comprised not only the emissions of harmful gasses and also the adverse consequences of the increased smog along with the reduction in fertility that leads to the detrimental health concerns to all living creatures.

Although there are numerous studies on concrete incorporating RHA, the majority of these address the engineering properties of the end product and not the sustainability indices when used in construction practice. For instance, Gursel et al. (2016) reported the implication of Life Cycle Assessment (LCA) on sustainable cementitious materials by considering the cradle-to-gate approach. Gastaldini et al. (2009), on the other hand, studied the unit cost of concrete incorporating RHA. It is reported that the increase in the unit cost of concrete when utilising RHA should not be considered alone as higher compressive strengths of concrete are attained compared to the conventional supplementary cementitious materials. Gastaldini et al. (2014) further stated that the cost of adding 5% RHA is less than 5% silica fume while taking several critical factors into account when computing the cost per cubic meter of concrete. Sua-iam and Makul (2014) also reported that when used as a fine aggregate replacement, the cost of concrete could reduce substantially compared to the control mixture. Brown (2012) also reported that the unit cost of the RHA is less than cement and that the replacement of RHA reduces the unit cost by around 43-51%. Later in 2018, Gill and Siddique also demonstrated that the unit price of concrete reduces with the replacement of RHA in concrete due to the lower unit prices of RHA compared to the cement binder. Moraes et al. (2010) exhibited the potential of LCA as an environmental tool which is used for the evaluation environmental sustainability of RHA utilization as mortar coatings. Later in 2013, Turner and Colins stated that the use of geopolymers provide high potential on reducing the carbon footprint of concrete. Turk et al. (2015) also reported that inclusions of different industrial by-products as cement or aggregate replacement provide environmental benefits such as pronounced reductions on the global warming potential, abiotic resource depletion potential of fossil fuels, acidification potential and eutrophication potential. The LCA results reported in Teixeira et al. (2016) has also shown that the use of 60% biomass fly ash as cement substitute improved the environmental performance of concrete. Fernando et al. (2021) also conducted a life cycle assessment on alkali-activated concrete comprising fly ash geopolymer and blended fly ash-rice husk ash and demonstrated that considerable reduction on the carbon footprint can be attained through this practice. Sathurshan et al. (2021) evaluated the life cycle assessment of concrete incorporating RHA as cement substitute. The results have shown that the incorporation of RHA in the range of 10–15% can be utilised to attain improved performance of environmental impact such as CO_2 emission, water pollution and eco-toxicity. Recently, Rigon et al. (2021) has also demonstrated that carbon footprint can be reduced significantly when 20% RHA, attained through the fluidized bed method, is used as a cement substitute in concrete. Despite these studies providing a significant insight into the use of RHA with respect to life cycle assessment and cost, there is a growing need to conduct a more comprehensive study reporting the consequences and the significances of the sustainable perspective of the RHA use in concrete manufacture.

The reduction in natural sources and extenuation of greenhouse gas (GHG) emissions interrelated with concrete production and construction activities are the emerging challenges in the construction industry. The global concrete production reached up to 10 billion tonnes in 2019 and is expected to rise to 18 billion tonnes by 2050 (Chatham House Report, 2018). The rapid growth in population and the accelerated demand for infrastructures are the main contributors for the dramatic increase in the global concrete production. Although cement comprises 20–40% of the total volume of concrete and/or cementitious mortar, cement manufacturing and processing are interrelated with the substantial CO_2 emissions (Mi et al., 2017; Buchs and Schnepf, 2013; Ince, 2019; Ince et al., 2020). Approximately 0.82 tonnes of CO_2 emissions are generated from the manufacture of 1 tonne of cement (Collins, 2010) and this contributes to approximately 5-6% of global CO_2 emissions. Cement production, known as the most energy-intensive production among all the manufacturing industries, necessitates high energy and high temperature for the calcination of limestone is a limited natural resource. Chatham House stresses the fact that we would require approximately 40% more clinker replacements by 2050 than that of today, particularity considering that the availability of the traditional substitutes may likely commence to fall at a time (Chatham House Report, 2018). Therefore, utilising RHA as a replacement to cement and/or to the raw materials strongly suggests a crucial reduction on the consumption of cement as well as the raw materials used for manufacturing mortar and concrete. The reduction on the consumption of the raw materials because of the utilization of RHA is significantly contributing to the reduction in the associated GHG emissions in addition to the energy required for processing (Sousa-Coutinho and Papadakis, 2011). Replacing raw materials with RHA also enables a significant decrease in the consumption of natural aggregates in construction. Insensate hazard mining and quarrying activities required to obtain the raw materials are at high risk of leading to adverse environmental consequences including, intrusions into the eco-system, wrecked landscape and pollution of air, water, and soil (Sathiparan and De Zoysa, 2018). For instance, the over exploration of the sand used in concrete making in Sri Lanka, resulted in diverse problems such as an increases in the depth of the riverbeds, lowering of the water table, and reduction of aquatic diversity (Sathiparan and De Zoysa, 2018).

This study assesses and re-evaluates the incorporation of RHA in concrete and examines the common sustainable indices including CO_2 emissions, cost efficiency and eco-strength efficiency. Findings are derived from a database containing over 1000 data points harvested from the literature reporting the use of RHA in concrete. The key factors that have an influence on the mechanical properties of concrete comprising RHA were investigated independently and comprehensively, these include, water: binder ratio, replacement type and level of RHA, the replacement type and level of pozzolans. The database approach adopted in the paper also enabled the reassessment of incorporation of RHA in concrete and significantly contributed to addressing the contradictory research findings among the published studies in the literature undividedly and effectively. This study demonstrates that the determination of the boundary conditions was vital to comprehend the first stage and hence enabled a successful reassessment on the sustainable indices to be conducted precisely. The paper demonstrates, for the first time, the key factors that affect both the mechanical properties and sustainable indices of the incorporation of RHA in concrete and offers important practical consequences for the construction practice and for the waste management corporations.

2. Development of the Rice Husk Ash (RHA) Database

The database developed focuses on RHA incorporation in concrete. Although there are many parameters affecting the performance of concrete including the origin and carbon content of RHA, pozzolanic activity index, the degree of amorphousness and fineness of the ash, the key factors such as the water:binder ratio, replacement types and levels of RHA and pozzolanic materials are observed to be the most prominently reported parameters affecting the performance of concrete within the context of the harvested papers used to develop the database in this study. The boundary conditions are attained through the database assessment using the aforementioned key factors as indicators to determine the optimal ranges of water: cement ratios, compressive strength values, the replacement type and level of RHA, the type of pozzolans used as well as the replacement level and type of pozzolanic materials in concrete. These boundary conditions were then employed in the assessment of CO_2 emissions, cost efficiency and the eco-strength efficiency.

The database comprises data for material mix constituents, water:binder ratio, replacement types and replacement levels of RHA and pozzolanic materials, the use of plasticisers, along with the short- and long-term strength of concrete incorporated RHA. The database used in the analysis for the construction of boundary conditions and then in the analysis of sustainability indices is shown in Table 1. Table 1 comprises the authors of the papers, number of data points used in each paper, compressive strength at 28 days and greater than 28 days, sand and cement replacement, replacement level of RHA, type and amount of pozzolans and plasticisers used in making concrete. The references used to construct the database are summarized in Appendix A.

The test data found in the literature was critically examined for completeness, test procedure and the RHA properties. For instance, data with missing information with regard to the mix constituents, replacement levels and replacement types of RHA, strength of concrete were omitted from the database. Studies failing to cite the relevant standards used for testing and inspecting are also not included in the database.

Establishing the allocated criteria was essential in obtaining a data set that was consistent and comparable. Criteria such as use of standard mix constituent materials, standard compressive strength data, RHA properties, replacement types and levels of RHA, type of pozzolans, replacement types and levels of pozzolans were therefore assessed in detail before a data set or a test result was included in the database. Figure 1 shows a flowchart that illustrates the method used to build the database in this study. A total of 1018 data points relating to concrete containing RHA were assembled. Of these, 64 experiments which did not fulfil the criteria for including data were disregarded for further evaluation.

3. Data analysis

CO_2 emissions, cost efficiency and eco-strength efficiency form the sustainability indicators examined in this study. The analysis of the CO_2 emissions accounts for the entire manufacturing and preparation processes of the individual components of the concrete including cement, fine aggregates and coarse aggregates. For instance, the CO_2 emission factor of cement used in this study includes the emissions generated from the fuel combustion, process-related emissions as well as the emission generated as a result of the fuel required to mine and transport the raw materials. Fuel combustion-related CO_2 emissions are derived from the clinker production and fuel used for pyro-processing. Process related emissions, on the other hand were generated from the chemical reactions that convert limestone to calcium oxide and CO_2. The CO_2 emission factor of cement is reported to be 0.82 kg CO_2/kg in Collins et al. (2010), Turner and Collins (2013), Diego et al. (2016), Geng et al. (2019), and more recently in Debbarma et al., (2020) and Chen et al (2022). Remarkably similar CO_2 emission factors of cement are also initailly reported by Huntzinger et al. (2009), Benhelal et al. (2013) and more recently in Huang et al. (2017) and Murmu et al. (2020). The CO_2 emission factor of cement therefore is accepted to be 0.82 kg CO2/kg in this study.

The CO_2 emission factors of fine and coarse aggregates also account for the extraction, cutting, grinding, sieving and transportation. The CO_2 emission factors of coarse and fine aggregates are reported to be 0.0459 kg CO_2/kg and 0.0139 kg CO_2/kg respectively in Flower and Sanjayan, (2007). More recently, Quattrone et al. (2014) provided CO_2 emission factor for coarse aggregates in similar ranges. Turner and Collins (2013) also provided the same CO_2 emission factor for fine aggregates.

The CO_2 emission factor of RHA and the pozzolans simply consider the grinding, preparation and sieving operations, the essential processes employed prior to the replacement of these materials in concrete. The CO_2 emission factor of RHA is reported to be 0.1032 kg CO_2/kg in Alnahhal et al. (2018). Prominently, very similar CO_2 emission factor of RHA is also recently reported in Selvaranjan et al. (2021). The CO_2 emission factors of pozzolans are largely reported in Yang et al (2013) are in a good agreement with Flower and Sanjayan (2007) who reported the CO_2 emission factor of slag is to be in the range of 0.052-0.143 kg CO_2/kg. The CO_2 emission factor of silica fume, initally reported in Flower and Sanjayan (2007) is also in a great agreement with the recently reported emission factor in Murmu et al. (2020). The CO_2 emission factor of silica fume and metakaolin are initailly reported in King (2012) and Hammond and Jones (2008) respectively. The associated emissions, also recently reported in Cassagnabere et al. (2010), Heath et al. (2014) as well as in Debbarma et al. (2020) along with Campos et al. (2020) are re-validated. The CO_2 emission factors, and the unit prices of the raw materials used in concrete making are summarised in Table 2.

Cost efficiency factor (CEF) is determined using the ratio of concrete compressive strength to the total cost of material per m^3 (Ince et al., 2021). The local prices of mix constituents, summarised in Table 2, were used to estimate the total cost of concrete and concrete containing RHA and pozzolans in US dollars. Therefore the total cost of concrete was calculated by multiplying the speficied raw material in the database, summarised in Table 1 with its associated CO_2 emissions factor, summarised in Table 2. The database provides the associated strength values of the corresponding specimens and therefore the cost efficiency factor could be computed using the ratio of compessive strength of concrete to the total cost of material. Eco-strength efficiency factor (ESEF) is then determined using the ratio of concrete compressive strength to CO_2 emissions of the materials per kg. The eco-strength efficiency factor was also determined based on the specified compressive strength values summarised in Table 1 along with the corresponding CO_2 emissions of each specimen. The total CO_2 emissions were also calculated based on the cummulative CO_2 emissions of each raw material used in the production of concrete specimens.

4. Results and Discussion

4.1 Factors affecting the RHA incorporation in mortars and concrete

The database approach adopted in the paper was used to investigate critical factors such as the water:binder ratio, replacement types and levels of RHA and pozzolans, that influence the short- and long-term performance of concrete containing RHA. The results enabled the independent determination of boundary conditions essential for the holistic reassessment of the sustainable analysis to be implemented precisely.

4.1.1 Water:binder ratio

Water: binder ratio, significantly influences the compressive strength of concrete comprising RHA, and is categorised under 3 distinct groups; water: binder ratio less than 0.3, water: binder ratio in the range of 0.3 to 0.6 and water: binder ratio greater than 0.6. 28-day compressive strength of concrete at all replacement levels are shown in Figure 2(a) comprising RHA with varying water:binder ratios. It should be noted that

Figure 2(a) consists of 954 data points representing the compressive strength however the majority of these (above 67%) represent concrete with water: binder ratio in the range of 0.3 – 0.6. Only 6% of the data points represent water: binder ratio less than 0.3. This is expected as the water: binder ratio less than 0.3 in concrete is usually impractical without the use of plasticisers. Water is essential for the consistence of the mixture at the plastic stage and for the hydration reaction to attain the ultimate properties of concrete at the hardened state. It is widely accepted that the water content required to proceed the chemical reactions is much less than the amount of water required to attain the standard consistence for workability. It should be noted that the water:binder ratio less than 0.3 shown in Figure 2(a) are the concrete samples often prepared using plasticisers to attain the required workability. 26% of the data demonstrated in Figure 2(a) uses a water:binder ratio greater than 0.6. It is clearly demonstrated that the rise in the water:binder ratio, irrespective of the substitution levels of RHA, caused a reduction in the compressive strength of the concrete. Results shown in Figure 2(a) clearly demonstrated that the rise in the replacement levels of RHA yielded a rise in the compressive strength of concrete at both water:binder ratios less than and equal to 0.3 as well as water:cement ratios in the range of 0.3 – 0.6. This trend is no longer valid when water:binder ratios were 0.6 and above. Increasing water content could be adopted to allow greater replacement levels of RHA to be incorporated in mixtures however, the excess water which is unnecessary for the chemical reactions often evaporates and form unwanted air pockets in the material’s matrix. This feature is mainly attributed to the reduction in the compressive strength of concrete containing particularly high substitution levels of RHA.

It is also noteworthy that the incorporation of RHA in concrete with water:binder ratios less than 0.3 was often not possible without the use of the plasticizers. High compressive strength of concrete particularly at high replacement levels were a result of plasticiser use. It should also be noted that very high water:binder ratios yielded a dramatic decrease in the strength of concrete incorporating RHA at higher substitution levels. Figure 2(a) shows that the use of RHA at replacement levels greater than 55% yielded in a substantial reduction in the compressive strength which was often lower than the minimum structural grade of 20MPa. Also, attaining very high compressive strength values particularly 100MPa could be achieved in a laboratory condition but this range is rarely met in practice. Therefore, the replacement levels greater than 55% and compressive strength values greater than 100 MPa are disregarded in the second attempt and are re-plotted in Figure 2(b). The number of data points was reduced from 954, shown in Figure 2(a) to 920 in Figure 2(b).

Confining the replacement levels with 55% and the compressive strength with 100MPa enabled presentation of a more authentic behaviour of concrete containing RHA with all water:cement ratios assessed in the paper. It should be noted that Figure 2(b) consists of 920 data points representing the 28-day compressive strength of concrete containing RHA. Water: cement ratios in the range of 0.3-0.6 provided the greatest fit line indicating the attainment of the best performance of concrete incorporating RHA. Although the water:cement ratios of 0.3-0.6 and the water:cement ratios less than 0.3 provided an accelerating gradient of compressive strength of concrete incorporated RHA, the concrete with water:cement ratios above 0.6

provided a decelerating gradient of compressive strength with rising replacement levels of RHA. Due to the decelerating gradient attained at water:cement ratios greater than 0.6 shown in Figure 2(b), the replacement ratios of RHA were re-examined. It was apparent that the increasing gradient of compressive strength of concrete with water:cement ratios above 0.6 only occurred when the substitution level of RHA was confined to 35%. The compressive strength of concrete comprising RHA at all water:binder ratios was replotted in Figure 2(c) and the replacement levels of RHA were limited to 35%.

Figure 2(c) comprises 883 data points in total where 5.5% of the data represents water:cement ratios less than 0.3 and 23.1% of the data represents water:cement ratios greater than 0.6. Therefore, most of the data points, above 71%, represent the 28-day compressive strength of concrete with water:cement ratios in the range of 0.3-0.6. Compared to Figures 2(a) and (b), increasing gradients of compressive strength of concrete at all water:binder ratios were obtained for the first time in Figure 2(c) when the replacement level of RHA were confined to 35%. The lower carbon content of the ash, obtained though the fluidized bed combustion, is essentially responsible from the high pozzolanic activity of the ash that enabled enhance compressive strength of concrete to be attained within the optimum range of replacement level of RHA (Venkatanarayanan and Rangaraju, 2015; Talsania et al., 2015; Nehdi and El Damatty, 2003; Zhang et al., 1996; Gastaldini et al., 2014; Rigon et al., 2021). The results shown in Figure 2(c) further demonstrated that very high replacement levels of RHA in concrete were often achieved by increasing the water:binder ratio or using a plasticiser which often resulted in adverse effects, particularity at the hardened state. The results presented in Figure 2(c) also correlate well with the studies in the literature that often report the optimum replacement levels of RHA to be in the range of 15% to 35% to attain the ultimate performance of concrete.

4.1.2 Replacement type:

Binder and sand replacements were the two types of replacement of RHA examined in this paper. 28-day compressive strengths of concrete comprising RHA used both as cement and sand replacements were plotted versus the replacement levels of RHA in Figure 3(a). Figure 3(a) comprises 915 data points of which more than 90% represent the compressive strength of concrete containing RHA used as a cement replacement at 28-day compressive strength. The rise in the substitution levels of RHA resulted in a decrease in the compressive strength of the concrete. It is also apparent that higher substitution levels of RHA ranging from 60 to 100%, used as sand replacement, are only reported at water:cement ratios greater than 0.6. As discussed previously, the rise in the water content, to attain the required consistence with high replacement levels of RHA, causes a remarkable diminution in concrete compressive strength. It is also demonstrated in Figure 3(a) that when the entire data is considered with all water:cement ratios, an authentic assessment of the effectiveness of the replacement types of RHA in concrete could not be performed. Therefore, the similar approach, previously pursued in the former section, is also adopted here. Hence, the water:binder ratios were limited to the range 0.3-0.6, replacement levels were confined to 35% and compressive strength values were maintained within the range 20-100 MPa in Figure 3(b).

The influence of the substitution type of RHA on the compressive strength of concrete was investigated using a total of 604 data points, presented in Figure 3(b). It is evident in Figure 3(b) that both replacement types examined in the paper had increasing effects on the compressive strength of concrete comprising RHA and that an increase in the substitution levels of RHA up to 35% had a methodical increase in the compressive strength. Figure 3(b) also demonstrates that the utilisation of RHA as a cement substitute had a greater influence in increasing the compressive strength of concrete compared to sand replacement. The great majority of the data (97%) collected from the literature were on the short-term compressive strength of concrete. Although the RHA often possessed high pozzolanic activity and hence its contribution to the development of definitive mechanical properties could only be seen over the long-term, the physical effects of RHA and therefore the associated influence on the physical properties on strength was demonstrated in Figure 3(b) alone. Although 46% of the studies, used to construct the database in this paper, reported the prevalence of the pozzolanic activity of the RHA, only ~3% of these reported the long-term properties of concrete containing RHA. It is widely accepted that the pozzolanic reaction, depending on the hydration reaction and more specifically the formation of the calcium hydroxide, progresses slowly and hence the actual influence of the pozzolans can only be observed over the long-term.

4.1.3 The use pozzolans:

The utilisation of pozzolans on the compressive strength of concrete incorporating RHA with water:binder ratios in the range of 0.3-0.6 is shown Figure 4(a). It should be noted that the compressive strength of concrete was confined to the range of 20 to 100MPa and that the replacement levels of RHA were limited to the 35%.

Figure 4(a) shows that the use of pozzolans yielded in a smaller rise in the compressive strength of concrete compared to the concrete specimens with no pozzolans. It should be emphasised again that most of the data (~97%) used in the database reported the short-term properties of concrete and hence the actual influence of the RHA and the additional use of pozzolans may not necessarily be reflected to the results shown in Figure 4(a). To gain an insight into the authentic performance of RHA and the additional use of pozzolans, the short- and long-term compressive strength of concrete comprising RHA along with the pozzolans were replotted in Figure 4(b).

Although the long-term results consist of only about 3% of the data points shown in Figure 4(b), it is evident that the long-term results enabled the actual performance of the pozzolans to be detected. It must be noted that the data points representing the long-term strength overlapped with those representing the short-term strength of concrete. Calcium hydroxide, formed during cement hydration reacted with silica phases within the pozzolans forming additional calcium-silica-hydrate gels entirely responsible from the development of strength. Long-term results relating to compressive strength of concrete 180 days and older demonstrated improved performance compared to the short-term. It should be noted however that Figure 4(b) comprises compressive strength of concrete incorporated RHA with varying types of pozzolans. The independent influence of the pozzolans on the strength of concrete was then investigated in Figure 4(c).

Nevertheless, out of the 954 data points used to construct the database in this paper, only 46% contained the incorporation of pozzolans in concrete following the set constraints. It is noteworthy that Figure 4(c) omits data points of concrete compressive strength less than 20MPa and higher than 100MPa, and RHA used as a sand replacement level higher than 35%. Nevertheless, out of 285 concrete specimens that contained pozzolans, the use of more than 10 different types of pozzolans were identified. In fact, the most commonly used pozzolans such as silica fume, fly ash, slag and metakaolin are taken into consideration to construct Figure 4(c). It is evident in Figure 4(c) that the use of slag and fly ash significantly contributed to the strength development of concrete whereas silica fume and metakaolin had less influence enhancing the compressive strength of concrete.

4.1.4 Boundary conditions

The designated key factors that significantly affected the performance of concrete incorporating RHA enabled the following boundary conditions to be established which were then applied for the evaluation of the sustainability indicators.

- The water:cement ratios in the range of 0.3 to 0.6 were found to provide the most accomplished strength values of concrete.

- Compressive strength values lower than 20MPa and greater than 100MPa were disregarded as they were not often practically acceptable and applicable to on site practice.
- It was recognized that substitution levels of RHA up to 35% increased the concrete strength and this value was therefore adopted for all water:binder ratios examined.
- The use of RHA as a cement substitute was found to provide higher compressive strengths of concrete compared to sand replacements.
- The use of pozzolans, particularly over the long-term, enabled greater strength of concrete to be attained.
- The utilization of fly ash and slag were more effective in increasing the compressive strength of concrete over the long-term.

The key findings outlined above formed the basis of the constrains employed to construct the feasible models that are used in the sustainability assessment in the latter section. These models encapsulate the concrete comprising RHA up to 35% and concrete comprising RHA up to 35% in conjunction with the pozzolans. The most commonly used pozzolans are designated to be silica fume, metakaolin, fly ash and slag that were used as cement substitute up to 35%. The models that comprised concrete containing RHA up to 35% used both as cement and sand replacement formed the next level of context. These models determined based on the boundary conditions enabled the assessment of the influence of RHA alone and RHA with pozzolans as well as the replacement type of RHA on the sustainability indices to be justifiably performed.

4.2 Sustainability Assessment

The database approach adopted in the paper was also utilized to investigate the effect of CO_2 emissions, the cost efficiency and the eco-strength efficiency of concrete incorporating RHA. The key factors that influence of the performance of concrete containing RHA, reported in the former section, enabled the independent determination of the boundary conditions. The implementation of these boundary conditions enabled a holistic reassessment of the sustainability analysis.

4.2.1 CO_2 emissions

The CO_2 emissions of concrete containing RHA as well as concrete containing both RHA and pozzolans are shown in Figure 5(a). The CO_2 emissions of a concrete control is also added for comparative purposes. It must be emphased that data points shown in Figure 5(a) represent only cement replacement of RHA up to 35% where the water:cement ratios were designated within the range of 0.3-0.6, the pozzolanic replacements were confined to silica fume, fly ash, slag and metakaolin. Specimen data points of concrete compressive strength lower than 20MPa and higher than 100MPa were omitted from the sustainability analysis and hence not considered in Figure 5(a).

It is evidently from Figure 5(a) that the rise in the binder substitution of RHA yielded in a substantial decrease in the CO_2 emissions of concrete. The significant decrease (~25%) attained in the CO_2 emissions of concrete is attributed to the considerable decrease in the cement consumption necessary to make up the corresponding concrete. In this case, the high CO_2 emissions of cement are partially replaced by the lower CO_2 emissions of RHA, therefore resulting in a substantial decrease in the process-related emissions. It should also be emphasised that the utilisation of RHA as a cement substitution also reduced the demand for cement manufacture and hence this further resulted in the reduction of fuel combustion and therefore contributed to reducing the carbon footprints. The use of pozzolans in conjunction with the RHA used as a binder replacement further reduced the necessity of cement and therefore accelerated the reduction of CO_2 emissions and likewise independently contributed to the carbon footprint recovery. It is also noteworthy that 587 data points, shown in Figure 5(a) were used in the CO_2 emission analysis of pozzolanic concrete containing RHA.

Figure 5(b) demonstrates the CO_2 emissions of concrete containing RHA used both as cement and sand substitutes. Figure 5(b) shows that the utilisation of RHA as a binder substitution considerably reduces the CO_2 emissions of concrete due to the aforementioned reasons. The incorporation of RHA as a sand substitute however does not positively influence the reduction of CO_2 emissions of concrete and in fact accelerates the CO_2 emissions further when compared to the control concrete. Although the use of RHA as a sand replacement could have an adverse impact on the carbon footprint generated due to concreting activities, devastation of natural assets to attain the essential aggregates in concrete production has harmful effects on the ecological sustainability. Substituting fine and coarse aggregates with RHA decreases the environmental damage and maintains ecological conservation.

CO_2 emissions are plotted versus the compressive strength of concrete and concrete comprising RHA in Figure 5(c). Figure 5(c) shows that the concrete (the control concrete) provided high CO_2 emissions over the entire range of compressive strengths examined in the database when compared to the concrete comprising RHA. This is to be expected as the control concrete contained a higher amount of cement compared to that of the concrete comprising RHA at all strength ranges which yielded high CO_2 emissions.

In addition to the substantial decrease in CO_2 emissions associated with the use of RHA over all concrete compressive strengths, Figure 5(c) also demonstrates that an increase in the compressive strength of both control and concrete comprising RHA improved the carbon footprint. The higher CO_2 emissions attained in these cases are attributed to the increased amount of binder and the raw materials used in making high strength concrete.

It must be noted that the considerable amount of CO_2 emissions generated in the course of the production of the raw materials is reabsorbed during the carbonation of cement based materials. Although there are conflicting rates reported by individual researchers in the literature (Xi et al., 2016; Yang et al., 2014; Wang et al., 2020), the average reabsorption rate is stated to be 43% between 1930 to 2013 (Xi et al., 2016). This suggests that the significant amount of CO_2 emitted during the production of the raw materials is reabsorbed during the lifespan of cement based materials.

4.2.2 Cost efficiency factor

The cost efficiency factor of concrete containing RHA as well as concrete containing both RHA and pozzolans are shown in Figure 6(a). The cost efficiency factor of the control concrete is also added in Figure 6(a) for comparison. It is previously shown in the paper that the incorporation of RHA as a cement substitute increases the strength of concrete. The use of pozzolans in conjunction with the RHA promotes the formation of calcium-silicate-hydrate gels and hence improves the hydraulic binding capacity of the matrix. Replacing the binder with RHA and pozzolans also reduces the total cost of the mixture as these materials have usually lower unit prices compared to the cement binder itself. Figure 6(a) reveals that the cost efficiency of concrete containing RHA is systematically increasing with the increased substitution level of RHA. The rise in the cost efficiency of concrete containing RHA is attributed to the significant rise in the strength of concrete and an accompanying reduction in the total cost of the mixture. The utilisation of pozzolans that further enhanced the strength of concrete and yielded a further decrease in the cost of such mixtures led to a 65% rise in the cost efficiency of concrete.

Figure 6(b) demonstrates the cost efficiency of concrete containing RHA when used as a substitute for both cement and sand. The utilisation of RHA as a binder substitute increased the cost efficiency of concrete due to the substantial increase in strength in conjunction with the decrease in the overall cost of these mixtures. The incorporation of RHA as a sand substitute did not improve the cost efficiency of the concrete as was the case for binder replacement. The reduction in the cost efficiency of concrete containing RHA as a sand substitute, compared to the case of binder replacement, is mainly attributed to the lower increase in strength as well as the lower reduction conquered in the total cost of the mixture. It must be emphasized in the paper that the performance of the replacement type of RHA is already examined in Section 4.1.2 and that cement replacements of RHA were reported to have more influential results on the strength of concrete. It is therefore unsurprising to observe that the utilisation of RHA as a cement substitute has considerably improved the cost efficiency of the concrete and that the adverse performance is exhibited in the case of the sand replacement.

4.2.3 Eco-strength efficiency factor

The eco-strength efficiency factor of concrete comprising RHA and concrete comprising both RHA and pozzolans are shown in Figure 7(a). The eco-strength efficiency factor of the control concrete was added in Figure 7(a) for comparison. The results show that the rise in the substitution level of RHA, utilised as cement substitute, resulted in a methodical increase in the eco-stren Sua-iam and Makul (2014) gth efficiency of the concrete. The substantial increase in strength as well as the associated reductions on the CO_2 emissions of the mixture, previously reported in the paper, acted simultaneously playing a determining role on the rise in the eco-strength efficiency of the concrete. The utilisation of pozzolans has already been shown to result in a substantial increase in strength and further reduction on the overall cost of the mixtures. These prominent factors further enhanced the eco-strength efficiency of pozzolanic concrete containing RHA.

It is shown in Figure 7(b) that use of RHA as sand replacements, did also not improve the eco-strength efficiency of concrete as much as in the case of the cement replacement. The results demonstrated in Figure

7(b) are in a good agreement with the results presented in Figure 7(b). The reduction in the eco-strength efficiency of concrete comprising RHA as a sand substitute, compared to the case of binder replacement, is mainly accredited to the lower increase achieved in the strength as well as the lower decrease in total CO_2 emissions of the mixture.

5. Conclusions

The paper begins with an assessment of the key factors that influence the mechanical properties of concrete incorporating RHA. Populating a large database was vital to gain an insight into the actual performance of RHA in concrete as well as to determine the boundary conditions that are essential to implement a meaningful analysis of sustainability. Sustainability components such as CO_2 emissions, cost efficiency and eco-strength efficiency attained during this practice are investigated in the paper for the first time. The key findings of this research are summarized herein:

- It is shown in the paper that the water:binder ratio played an indispensable role in determining the optimal replacement level of RHA. The results have revealed that the water:binder ratio in the range of 0.3 to 0.6 were found to provide the most accomplished strength values of concrete containing RHA. The database study also indicated that compressive strength values lower than 20MPa and greater than 100MPa were not practical for use on site and therefore disregarded in this study. The most effective replacement type was identified as RHA up to a 35% replacement level. The use of pozzolans demonstrated a clear enhancement on the strength of concrete containing RHA. The fly ash, silica fume, metakaolin and slag were designated as the most commonly used and effective pozzolanic additions to concrete containing RHA.

- Key factors, the water:binder ratio, replacement types and levels of RHA and pozzolanic materials are observed to be the most prominently reported parameters affecting the performance of concrete containing RHA, played a crucial role in the determination of the boundary conditions necessary for the precise assessment of the sustainability analysis.

- The results have shown that the use of RHA in conjunction with the pozzolans as cement replacement had a dramatic influence in reducing the carbon footprint significantly. This is attributed to the reduced demand of cement that results in a substantial decrease in the process-related emissions as well as fuel combustion and therefore essentially contributes to reducing the carbon footprint.

- Cost efficiency and eco-strength efficiency of concrete have shown to improve significantly when incorporated with RHA and pozzolans. The substantial increase in strength and the associated reduction in the associated CO_2 emissions, as well as the reduction in the total cost of such mixtures were the decisive mechanism responsible from this phenomenon.

- Although reducing the clinker-to-cement ratio and the deploying innovative technologies could dramatically improve the sustainable manufacture of cement, the latter often is not the optimal case in developing countries. This paper reports important results regarding the reduced clinker-to-cement ratio and hence contributes to the reduction of the most direct emissions in this context.

- Considering that the rice industry generates approximately 156 million tons of rice husk annually, the waste disposal method, addressed in the paper, should not be underestimated particularly when compared to the existing waste management alternatives that often cause contamination and pollution.

- The research results demonstrated in this paper reinforce the resources that can basically be implemented for the sustainable development of concrete in construction practice.

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Table 1

Table 1: The database context

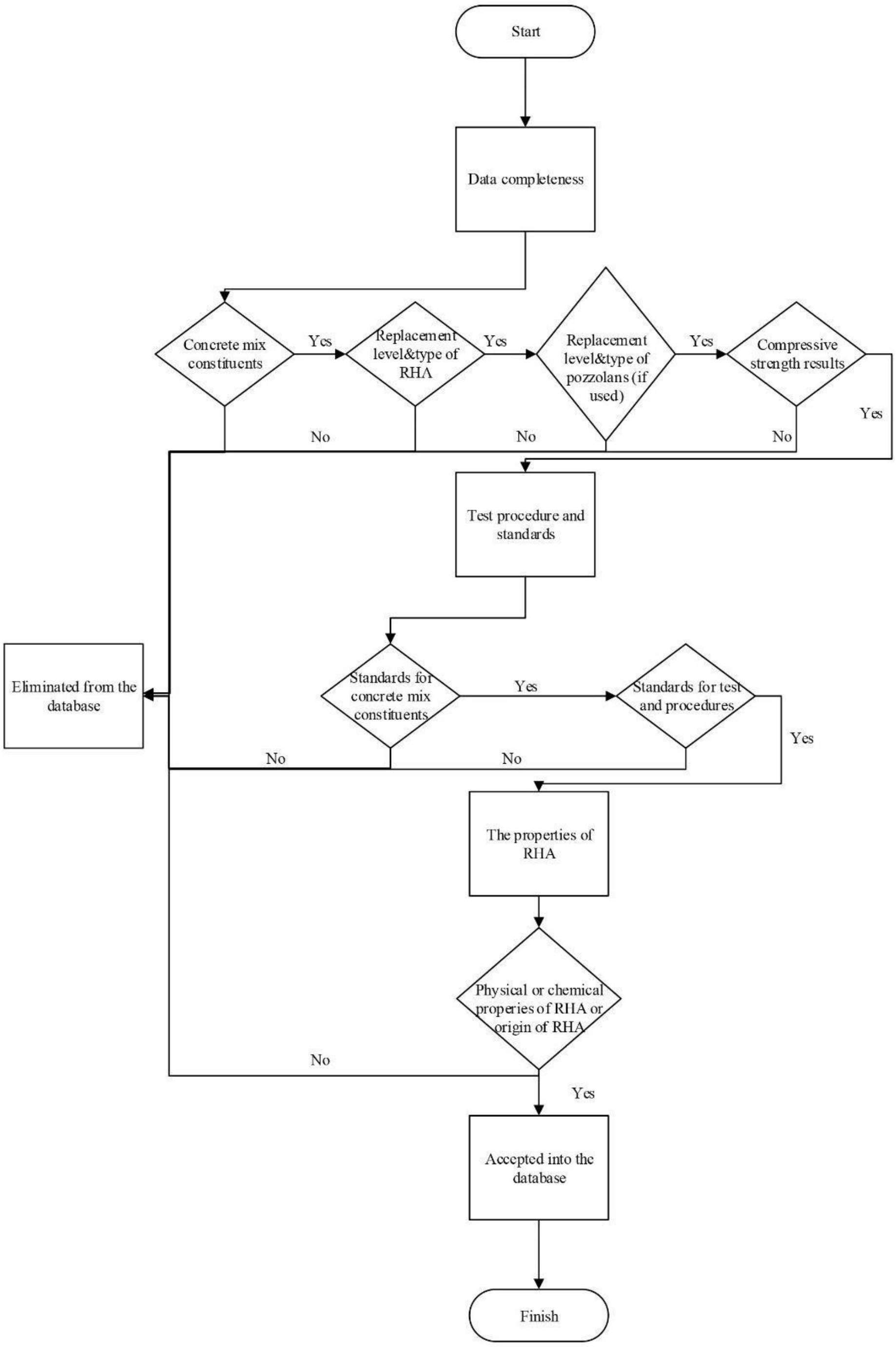
#	Author	Year of Publication	# of data	Compressive strength (MPa) (<28 days)	Compressive strength (MPa) (28 days)	Compressive strength (MPa) (>28 days)	Sand/Cement Replacement	RHA Replacement Range (%)	Pozzolan Type	Pozzolan Amount (Range %)	Plasticizer type	Plasticizer Amount
1	Gursel et al.	2016	9	15-48	48-68	54-69	Cement	10-20	Fly Ash and Limestone Flour	30-45	Superplasticizer	2.6-4.8
2	Le et al.	2014	6	37-57	54-62	-	Cement	5-20	SF	0-10	Superplasticizer	0.5-0.6
3	Koushkbaghi et al.	2019	12	40-56	43-63	48-68	Cement	0-20	-	-	High-range waterreducing	4
4	Muthukrishnan et al.	2019	6	49-62	55-71	60-80	Cement	0-20	-	-	Superplasticizer	6.3-8
5	Givi et al.	2010	9	22-28	37-44	41-51	Cement	5-20	-	-	-	-
6	Jindal and Ransinchung	2018	11	16-28	36-41	-	Mineral Addition	5-15	Fly Ash and Bagasse Ash	5-15	Superplasticizer	2
7	Kannan and Ganesan	2014	17	28-29	37-57	-	Cement	5-30	Metakaolin	5-30	Superplasticizer	8
8	Makul	2019	28	13-69	29-83	32-97	Cement	10-20			Superplasticizer	6.5-33.6
9	Sathawane et al.	2013	8	18-39	29-46	31-50	Cement	2.5-15	Fly Ash	15-30	Superplasticizer	5.7-7.7
10	Salas et al.	2009	10		34-42	37-53	Cement	5-20	Silica Fume	0-10	Superplasticizer	1.8-17.6
11	Zerbino et al.	2011	15	5-33	10-44	13-57	Cement	15-25			Superplasticizer	0.2-1.7
12	Chatveera and Lertwattanaruk	2011	27		10-29		Cement	20-40				
13	Gill and Siddique	2018	4	28-38	41-52	45-72	Fine Aggregate	0-10	Metakaolin	5-15	Superplasticizer	7.2-9.6
14	Makul and Suaiam	2018	24	8-42	20-45	21-53	Cement	0-20	Urea	5-20	High-range waterreducing	0.2-8.2
15	Venkatanarayanan and Rangaraju	2015	7	29-51	43-61	47-66	Cement	7.5-15	Silica Fume	7.5-15	Superplasticizer	2.1-5.5
16	Sua-iam and Makul	2012	6	10-57	28-51		Fine Aggregate	5-20			High-range waterreducing	11
17	Le and Ludwig	2016	8	35-96	109-118	117-129	Cement	5-20	Silica Fume and Fly Ash	30-40	Superplasticizer	13.3-15.6
18	Talsania et al.	2015	9	6-10	8-11		Cement	10-20				
19	Mahmud et al.	2016	4	31-106	94-113	99-114	Cement	10-20			Superplasticizer	3.1-4
20	Chao-Lung et al.	2011	6	16-63	47-66	51-74	Cement	10-30			Superplasticizer	0.3-3.7
21	Lertwattanaruk et al.	2018	28	16-53	24-59	25-62	Cement	0-20	Calclium Carbonate	20-40	HRWR	11-13
22	Olutoge and Adesina	2019	6	13-41	23-41	25-54	Cement	5-15				
23	Foong et al.	2015	20	15-47	44-52		Cement	5-20			Superplasticizer	3.3-6.6
24	Patel and Shah	2018	5	5-38	20-43		Cement	5-25			Superplasticizer, NaOH, Na-silicate	15,8
25	Chatveera and Lertwattanaruk	2014	18		19-45		Cement	10-50			HNO3 and CH3COOH	10
26	Chatveera and Lertwattanaruk	2009	16	20			Cement	10-50				
27	Cordeiro et al	2012	8	15-55	21-70	29-76	Cement	0-20	Sugar cane Bagasse Ash	0-20	Superplasticizer	0.5-2.4
28	Zareei et al.	2017	6	35-42	51-60		Cement	5-25	0	10	Superplasticizer	15
29	Muthadhi and Kothandaraman	2013	19	31-72	43-87	49-92	Cement	10-30			Superplasticizer	0.9-11
30	Safiuddin and Soudki	2010	15	30-72	42-95	45-100	Cement	5-30			High-range waterreducing and AEA	1.7-10.6
31	Gastaldini et al.	2010	19		17-72	24-86	Cement	10-35	Slag and Fly Ash	35-50	Superplasticizer	0.1-2.9
32	Padhi et al.	2018	16	10-30	18-41	22-44	Cement	5-35			Superplasticizer	3,7

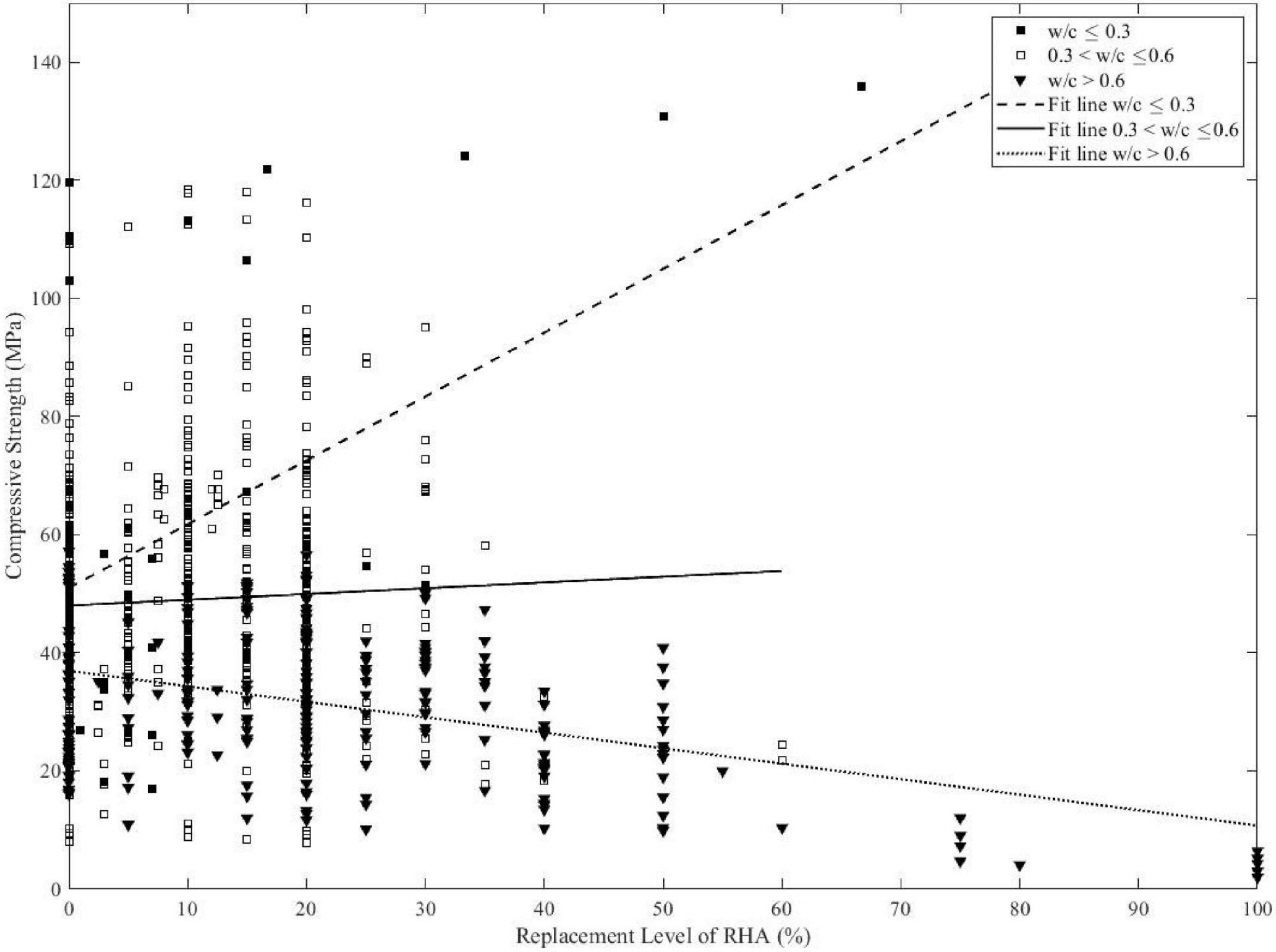
33	Kunchariyakun et al.	2018	5	13-18			Sand	30-50	Lime	4	Superplasticizer	
34	Huang et al.	2017	6	88-96	120-136	125-137	SF Replacement	17-83	Silica Fume	17-100	Superplasticizer	19,1
35	Raisi et al.	2018	5		48-58		Cement	5-20			Superplasticizer	4.5-9.2
36	Tangchirapat et al.	2008	13	25-37	35-51	38-58	Cement	20-50			Superplasticizer	1.7-3.3
37	Gastaldini et al.	2009	18		17-72	24-86	Cement	10-30	Slag and Fly Ash	35-50	Superplasticizer	0.4-9.5
38	Horsakulthai et al.	2011	7	16-30	21-40	29-53	Cement	10-40			Superplasticizer	1-6.4
39	Bahri et al.	2019	5	35-96	86-113	91-115	Cement	10-20	Silica Fume	0-10	Superplasticizer	2.4-4.2
40	Raisi et al.	2018	17	25-36	29-65	64-74	Cement	5-20			Superplasticizer	2.7-9.8
41	Madandoust et al.	2011	7		27-35		Cement	5-30			Superplasticizer	3.8-4.6
42	Mahmud et al.	2009	15	19-60	41-69		Cement	5-20			Superplasticizer	0.6-4.4
43	Madandoust and Ghavidel	2013	13	13-40	25-45	48-58	Cement	5-20	Glass Powder	10-25	Superplasticizer	0.4-4.6
44	Modarres and Hosseini	2014	12	6-33	11-40	19-46	Cement	3-5			Superplasticizer	
45	Mohseni et al.	2016	13	26-34	45-58	54-65	Cement	5-15	0	1-5	Superplasticizer	4.2-8
46	Sua-iam et al.	2016	4	16-38	38-45		Cement	10-20	Lime Stone	10-20	Superplasticizer	9
47	Ameri et al.	2019	10	29-39	38-50	46-67	Cement	5-30	Bacteria content addition, Limestone and Micro silica	28	Superplasticizer	14
48	Bui et al.	2005	24	19-67	58-98	65-107	Cement	10-20			Superplasticizer	5-7.5
49	Nehdi et al.	2003	18	25-37	54-72		Cement	7.5-12.5	Silica Fume	7.5-12.5	High-range waterreducing	1.5-4
50	Mohseni et al.	2016	26		39-53	44-60	Cement	7.5-12.5	Nanoalumina	1-3	SP	0.9-4.5
51	Siddique et al.	2016	10	21-26	33-40	39-47	Cement	5-20	Bacillus aerius	10^5 cells/mL		
52	Zareei et al.	2017	6	51-57	83-93		Cement	5-25	Micro-silica	8-10	Plasticizer: poly carboxylic	15
53	Ganesan et al.	2007	8	26-39	35-43	37-46	Cement	5-35				
54	Zhang et al.	1996	3	41-65	61-79	71-82	Cement	0-10	Silica Fume	0-10	Superplasticizer	6.9-9.6
55	Rahman et al.	2014	4	21-37	34-49		Cement	20-40			Superplasticizer	3.7-8.8
56	Kannan	2018	26		31-45	35-47	Cement	5-30	Metakaolin	5-30	Superplasticizer	7.6-9.5
57	Gill and Siddique	2017	16	19-38	30-52	46-72	Fine Aggregate	10-30	Metakaolin	5-15	Superplasticizer	4,2
58	Abalaka	2013	20	17-54	29-56	34-66	Cement	5-25				
59	Chindaprasirt et al.	2007	9		18-28	22-29	Cement	20-55	Fly Ash	20-40		
60	de Sensale	2006	15	21-51	32-60	35-69	Cement	10-20			Superplasticizer	0.1-2.1
61	Chopra et al.	2015	4	29-36	37-49	40-54	Cement	10-20			Superplasticizer	5,5
62	Praveenkumar et al.	2019	7	23-27	36-41	43-48	Cement	0-10	0	1-5		
63	Mehta and Siddique	2018	7	48-62	51-67	53-69	GGBS	5-30			Superplasticizer and Alkali solution	166
64	Gastaldini et al.	2014	21		32-73	37-81	Cement	5-30	Silica Fume	5-10	Superplasticizer and Plasticizer chemical admixture	0.9-12.1
65	Cordeiro et al.	2009	4	52-55	61-70	69-77	Cement	10-20			Superplasticizer	1.4-2.4
66	Sua-iam and Makul	2013	7	7-45	21-61	26-69	Cement	10-40	Fuel Ash	10-20	Superplasticizer	11
67	Anwar et al.	2000	3	2-21	21-31	27-42	Cement	10-20				
68	Sua-iam and Makul	2014	20	1-42	3-53	5-72	Fine Aggregate	25-100	Fly Ash	20-60	High-range waterreducing	5.5-6.6
69	Sua-iam and Makul	2013	25	0.5-62	2-68	3-83	Fine Aggregate	10-100			Superplasticizer	11

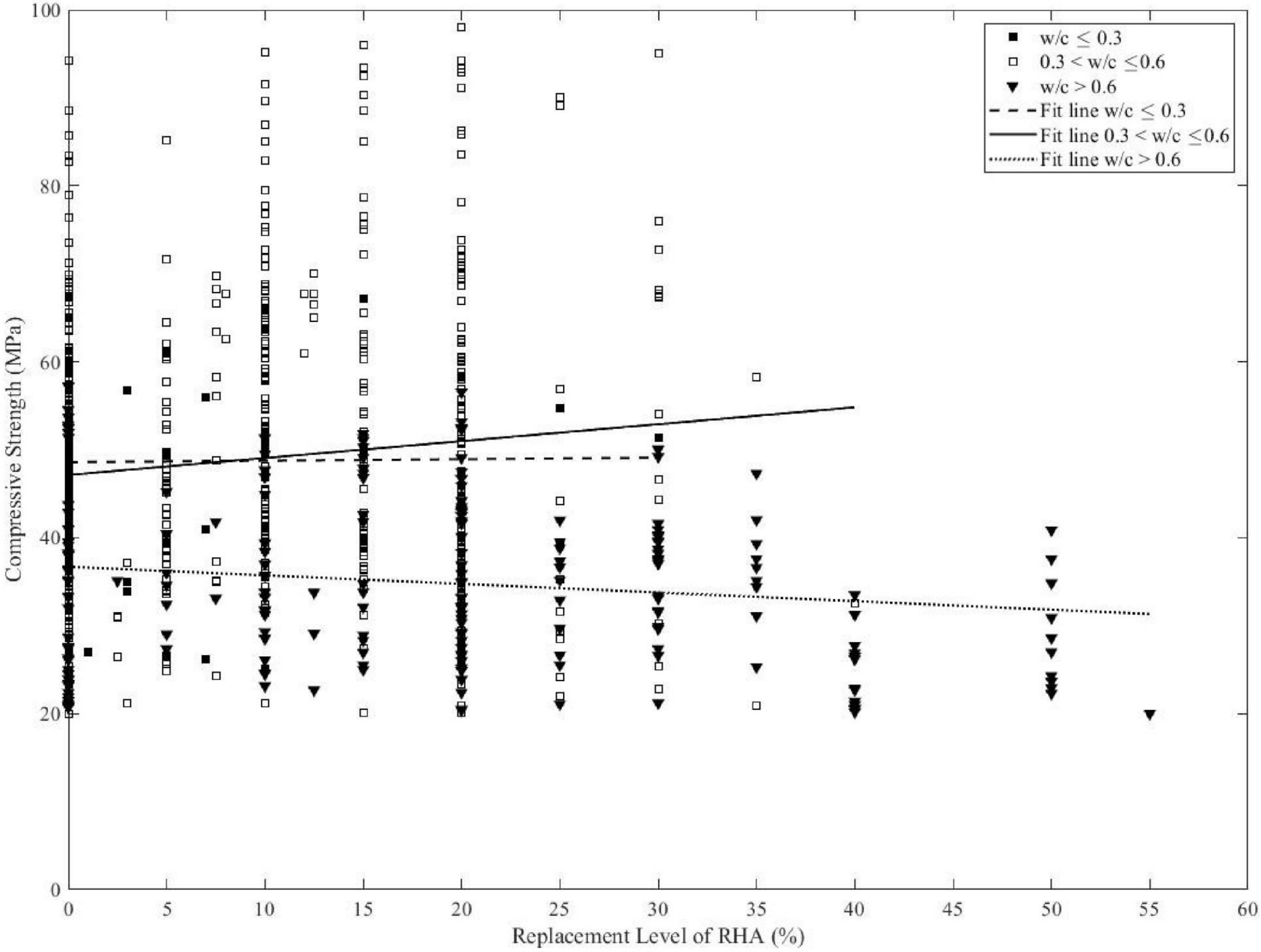
70	Chalee et al.	2013	10		29-45	29-46	Cement	15-50			Superplasticizer	0.3-3.8
71	Sua-iam et al.	2019	14	15-46	34-55	38-65	Cement	10-20			Superplasticizer	6.4-27.8
72	Rattanachu et al.	2020	9	16-36	22-46	24-49	Cement	20-50			Superplasticizer	0.4-1.7
73	Kusbiantoro et al.	2012	9	7-55	17-57	17-71	Fly Ash	3-7			NaOH and Na 2SiO3 Solution	144
74	Krishna et al.	2016	5	12-20	16-29		Cement	5-20				
75	Naveen et al.	2015	10	28-54	9-70		Cement	5-20				
76	Prayuda et al.	2020	16	6-36	19-40		Fine Aggregate	20-60	Silica Fume	0-5	Superplasticizer	4,85
77	Zubairu et al.	2018	9	11-27	13-27	20-34	Cement	2.5-20	0	2.5-10		
78	Nair et al.	2013	15	42-67	67	68	Cement	10-25			Superplasticizer	1.7-9
79	Hussain et al.	2019	8	37-52	41-60		Cement	10-20			0	4.5-8
80	Amin et al.	2019	4		42-44		Cement	10-20			Superplasticizer	5.1-7.1
81	Vieira et al.	2020	5	51-63	58-68	69-73	Cement	8-12			Superplasticizer	2.9-4.5
82	Das et al.	2020	6	12-29	25-39		Fly Ash	1-10	0	63-70	Alkaline Liquid	147
83	Sakr	2006	30	30-42	43-57	48-70	Cement	5-20	Silica Fume	5-20	Superplasticizer	22.5-30
84	Lun	2015	10	22-32	31-40		Cement	2.5-10			Plasticizer	4,69
85	Brown	2012	23	0.4-26			Cement	10-40				

Table 2: CO_2 emission factors and the unit prices of constituent materials

Constituent materials	CO_2 emission factor (kg CO_2/kg of the material)	Cost (local price in $)
Portland cement	0.82 (Collins et al. 2010)	$0.11/kg
Coarse Aggregates	0.0459 (Flower and Sanjayan, 2007)	$0.008/kg
Fine Aggregates	0.0139 (Flower and Sanjayan, 2007)	$0.0075/kg
Rice Husk Ash (RHA)	0.1032 (Alnahhal et al. 2018)	$0.015/kg
Silica fume	0.028 King (2012)	$0.095/kg
Metakaolin	0.330-0.423 (Hammond and Jones, 2008)	$0.093/kg
Fly ash	0.004-0.027 (Flower and Sanjayan, 2007)	$0.080/kg
Slag	0.052-0.143 (Flower and Sanjayan, 2007)	$0.072/kg


Start
Data completeness
Concrete mix constituents
Yes
Replacement level&type of RHA
Yes
Replacement level&type of pozzolans (if used)
Yes
Compressive strength results
Yes
No
No
No
Test procedure and standards
Eliminated from the database
Standards for concrete mix constituents
Yes
Standards for test and procedures
Yes
No
No
The properties of RHA
Physical or chemical properies of RHA or origin of RHA
No
Yes
Accepted into the database
Finish


Compressive Strength (MPa)
0
20
40
60
80
100
120
140
0
10
20
30
40
50
60
70
80
90
100
Replacement Level of RHA (%)
w/c ≤ 0.3
0.3 < w/c ≤0.6
w/c > 0.6
Fit line w/c ≤ 0.3
Fit line 0.3 < w/c ≤0.6
Fit line w/c > 0.6


Compressive Strength (MPa)
0
20
40
60
80
100
Replacement Level of RHA (%)
0
5
10
15
20
25
30
35
40
45
50
55
60
■ w/c ≤ 0.3
□ 0.3 < w/c ≤0.6
▼ w/c > 0.6
Fit line w/c ≤ 0.3
Fit line 0.3 < w/c ≤0.6
Fit line w/c > 0.6

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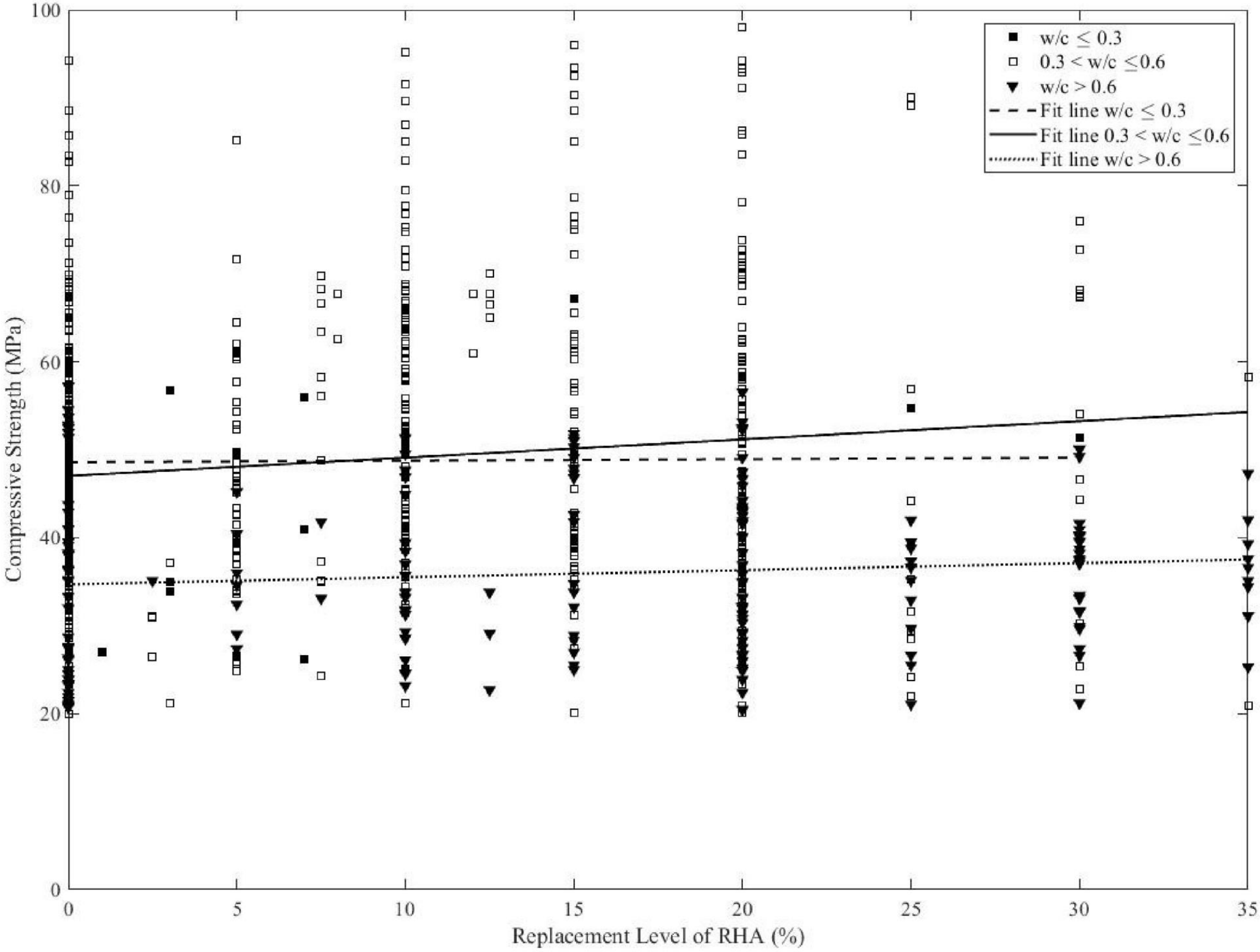

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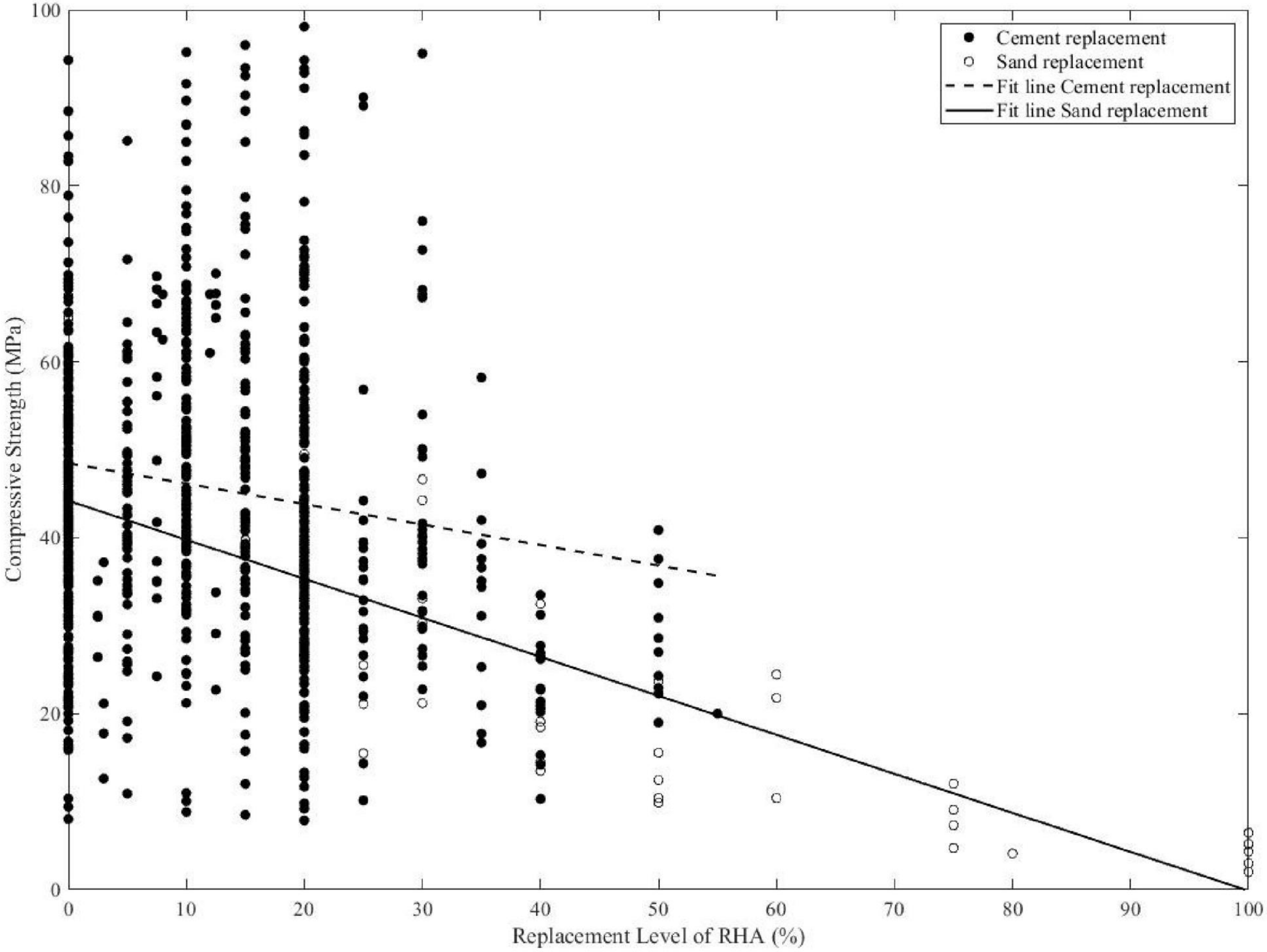

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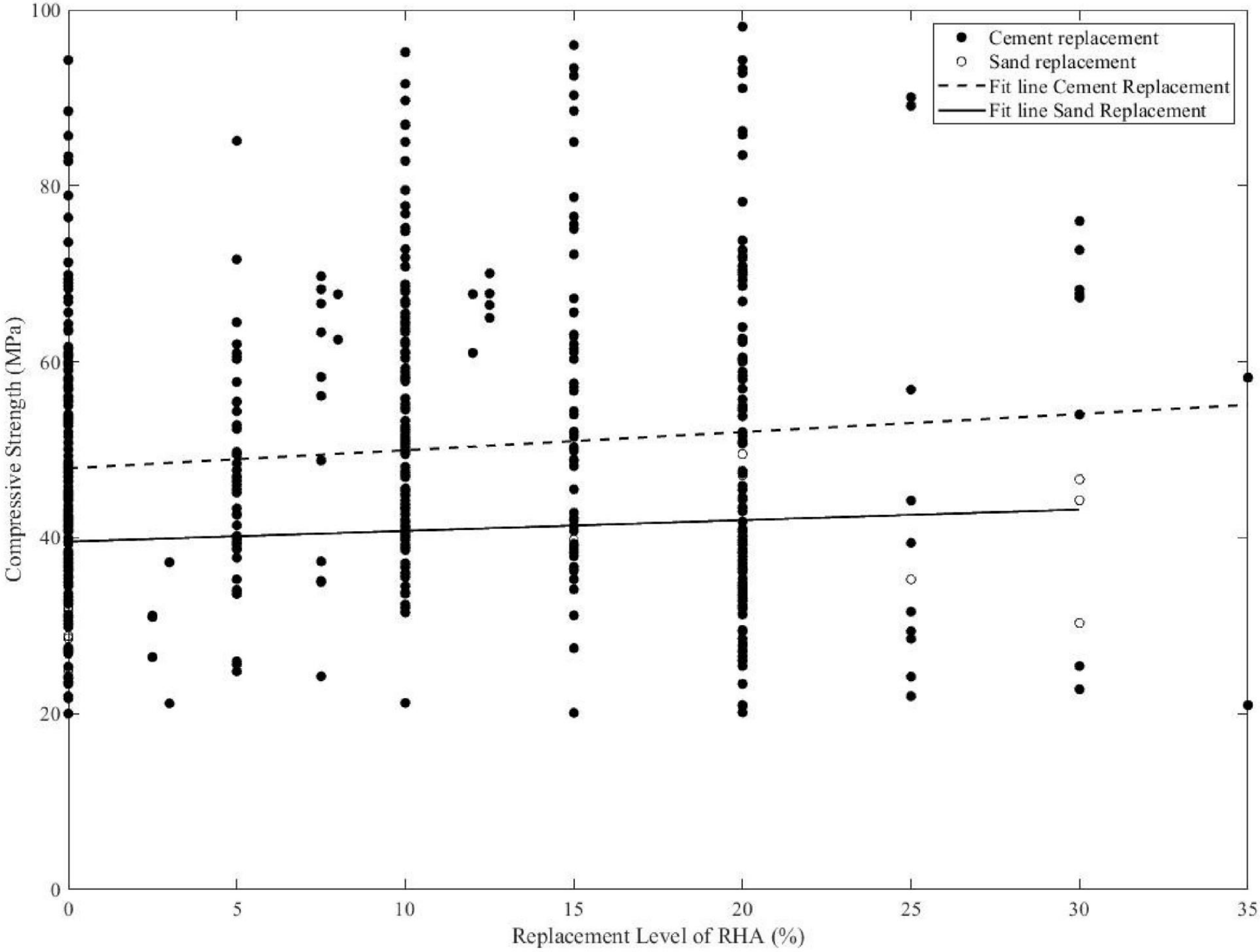

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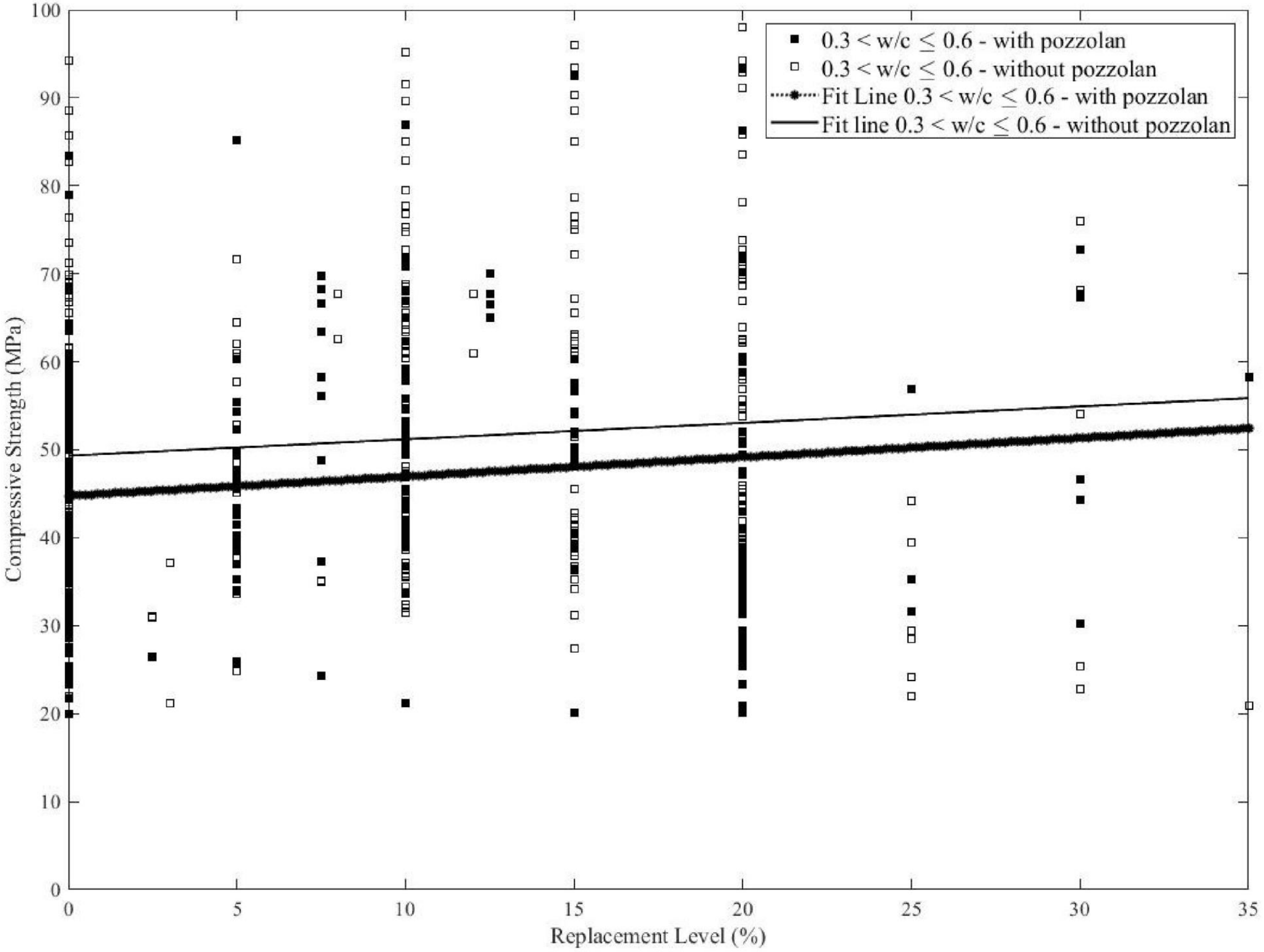

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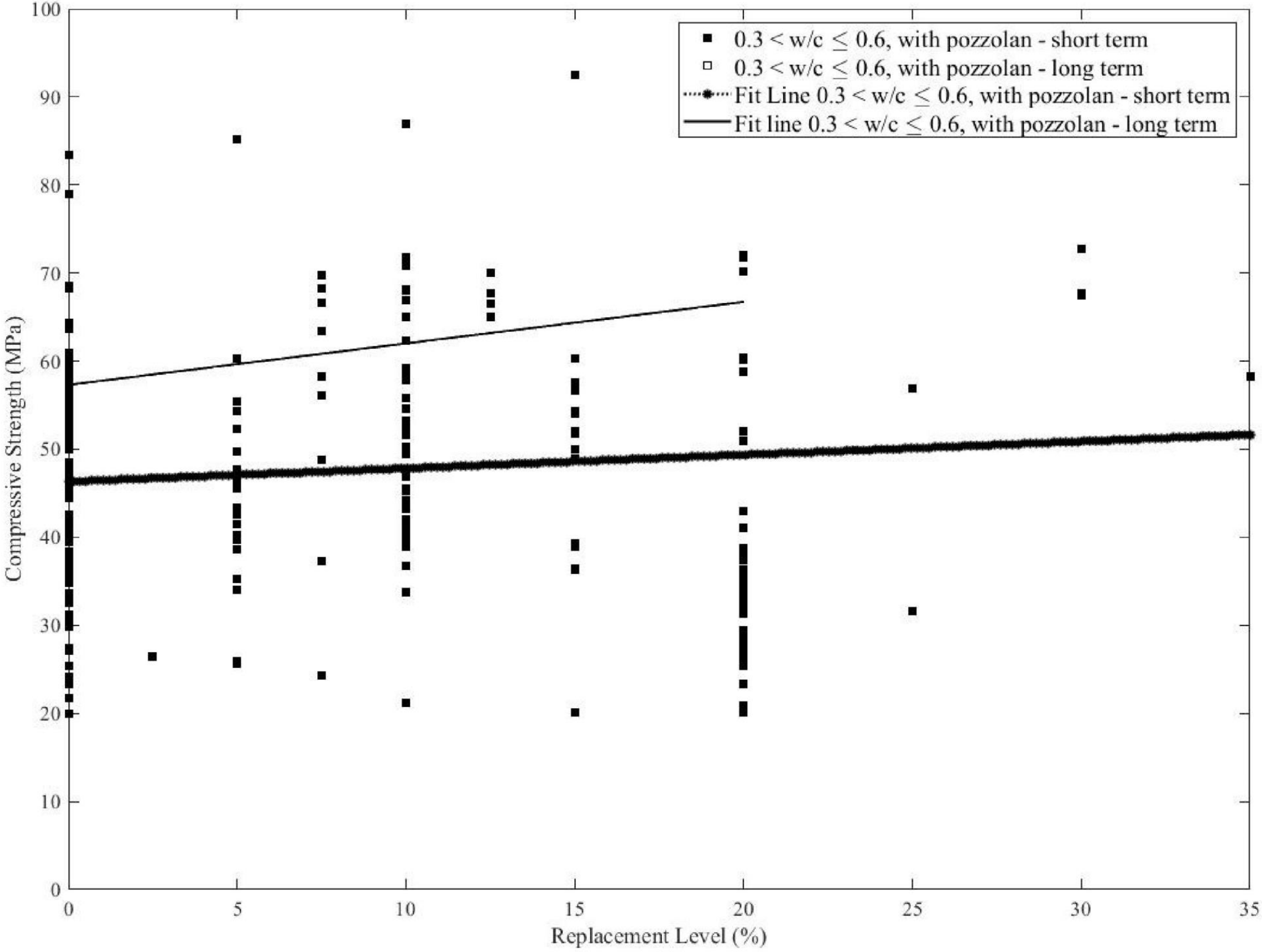
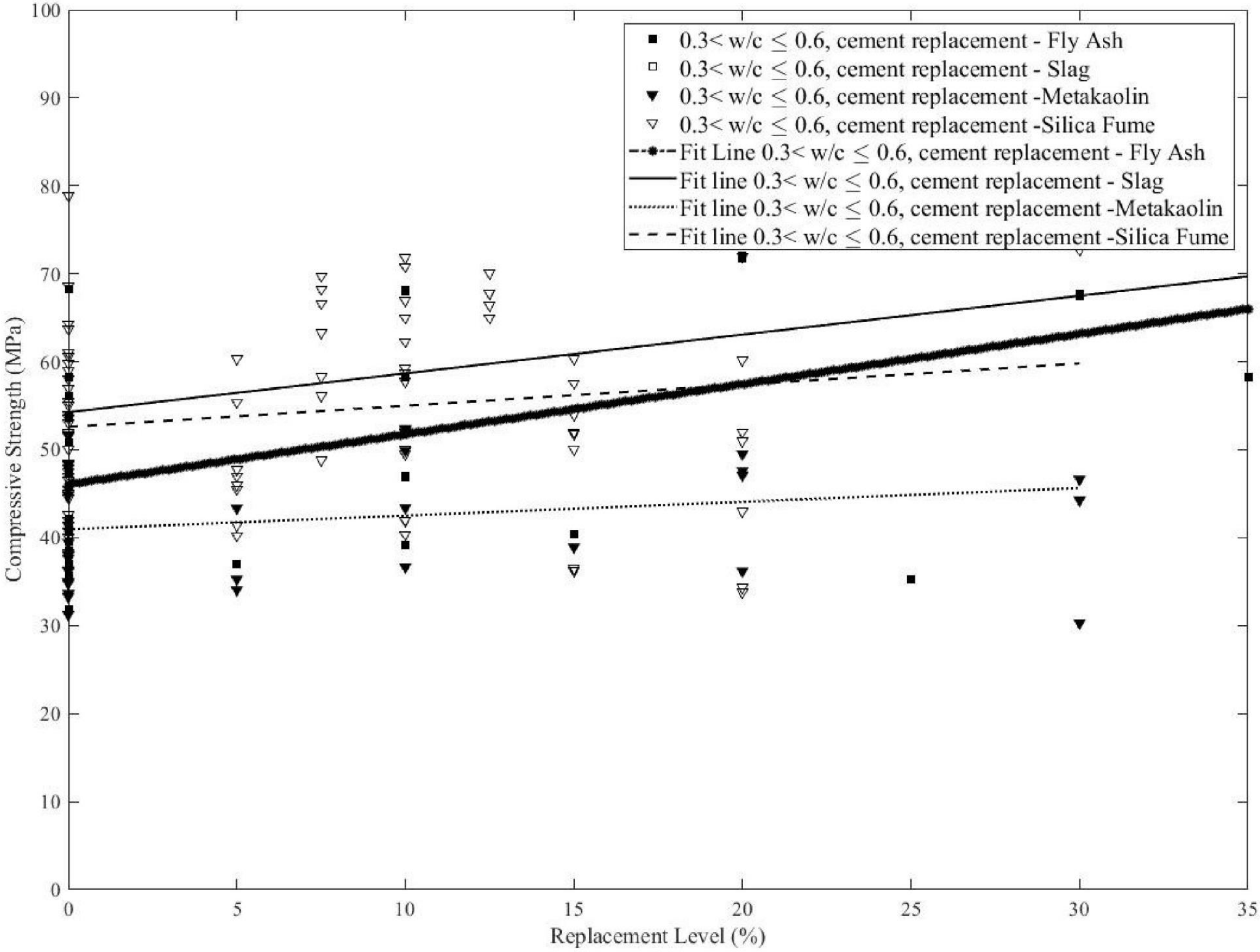
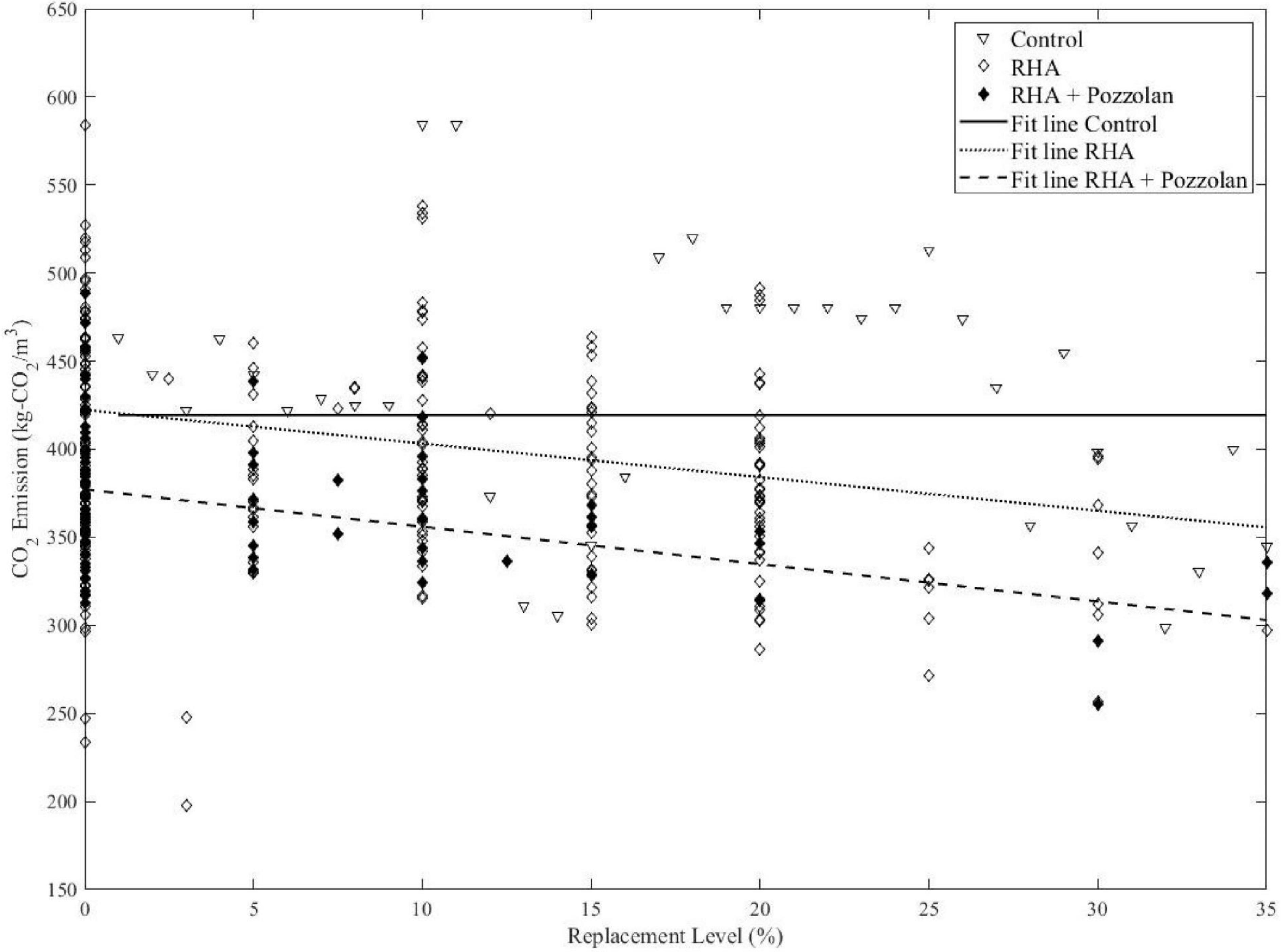
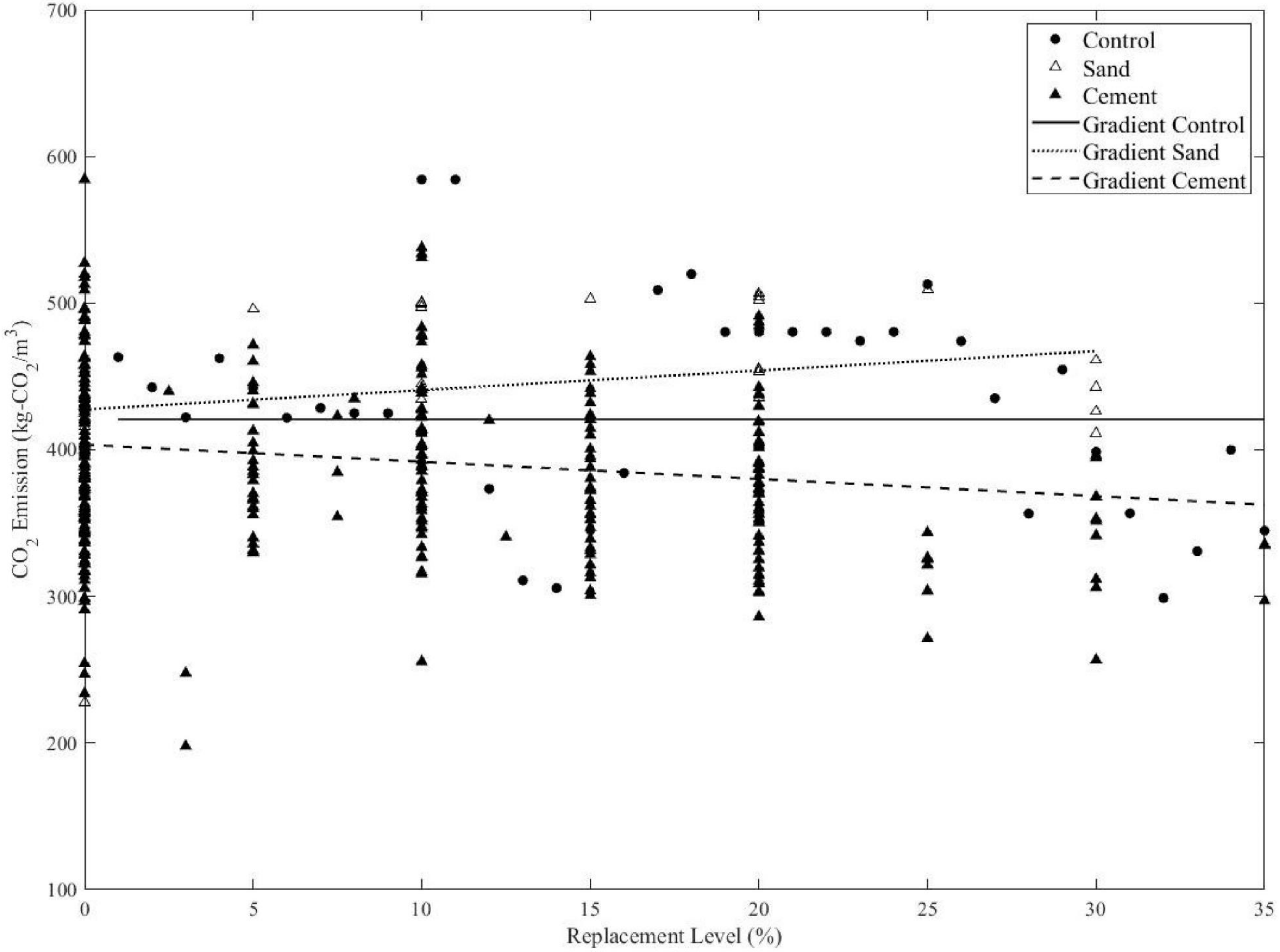
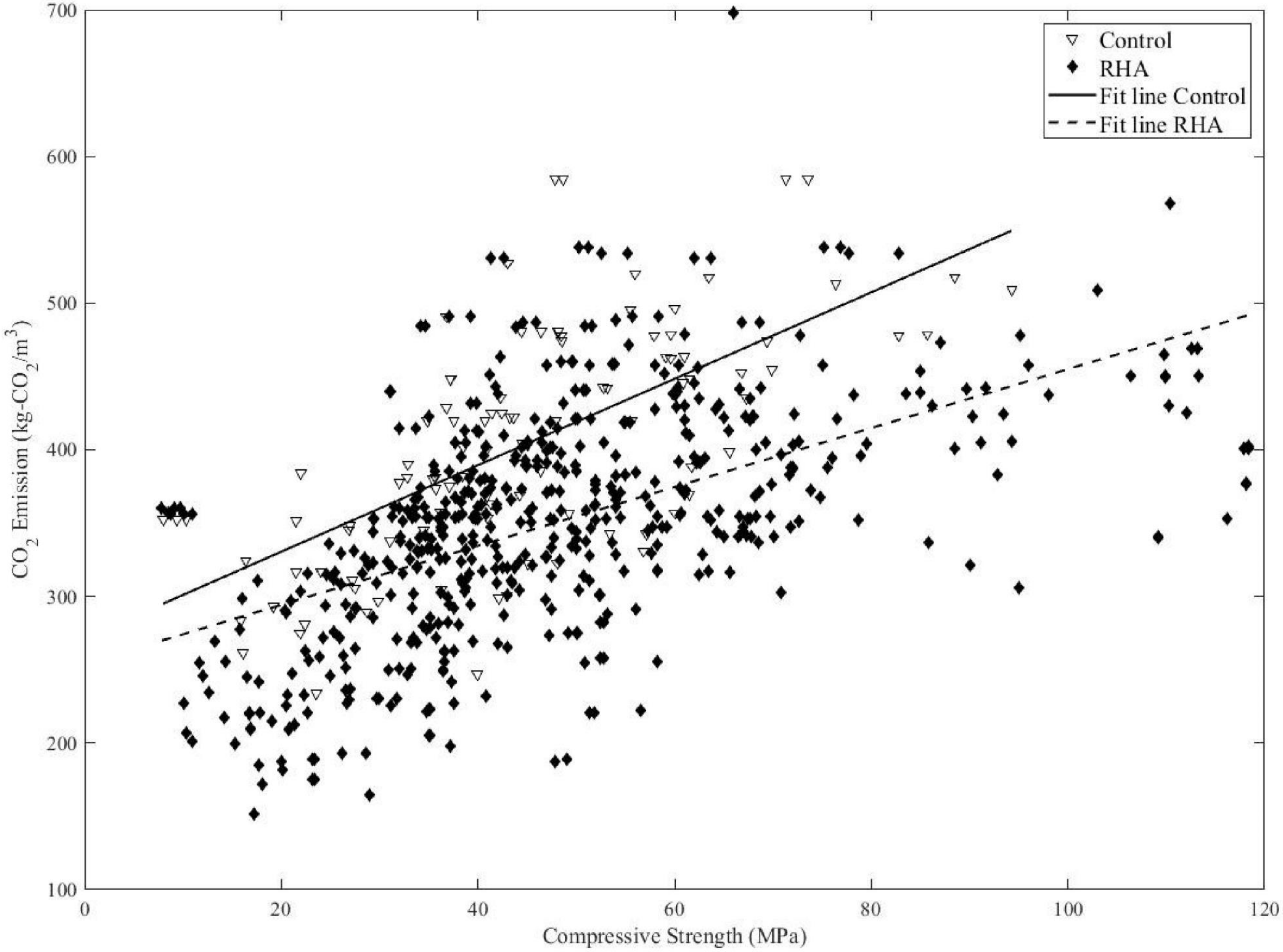



■ 0.3< w/c ≤ 0.6, cement replacement - Fly Ash
□ 0.3< w/c ≤ 0.6, cement replacement - Slag
▼ 0.3< w/c ≤ 0.6, cement replacement -Metakaolin
▽ 0.3< w/c ≤ 0.6, cement replacement -Silica Fume
Fit Line 0.3< w/c ≤ 0.6, cement replacement - Fly Ash
Fit line 0.3< w/c ≤ 0.6, cement replacement - Slag
Fit line 0.3< w/c ≤ 0.6, cement replacement -Metakaolin
Fit line 0.3< w/c ≤ 0.6, cement replacement -Silica Fume
Compressive Strength (MPa)
Replacement Level (%)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30
35


650
600
550
500
450
400
350
300
250
200
150
0
5
10
15
20
25
30
35
CO_2 Emission (kg-CO_2/m^3)
Replacement Level (%)
Control
RHA
RHA + Pozzolan
Fit line Control
Fit line RHA
Fit line RHA + Pozzolan

Click here to view linked References




Control
RHA
Fit line Control
Fit line RHA
CO$_2$ Emission (kg-CO$_2$/m^3)
Compressive Strength (MPa)
100
200
300
400
500
600
700
0
20
40
60
80
100
120

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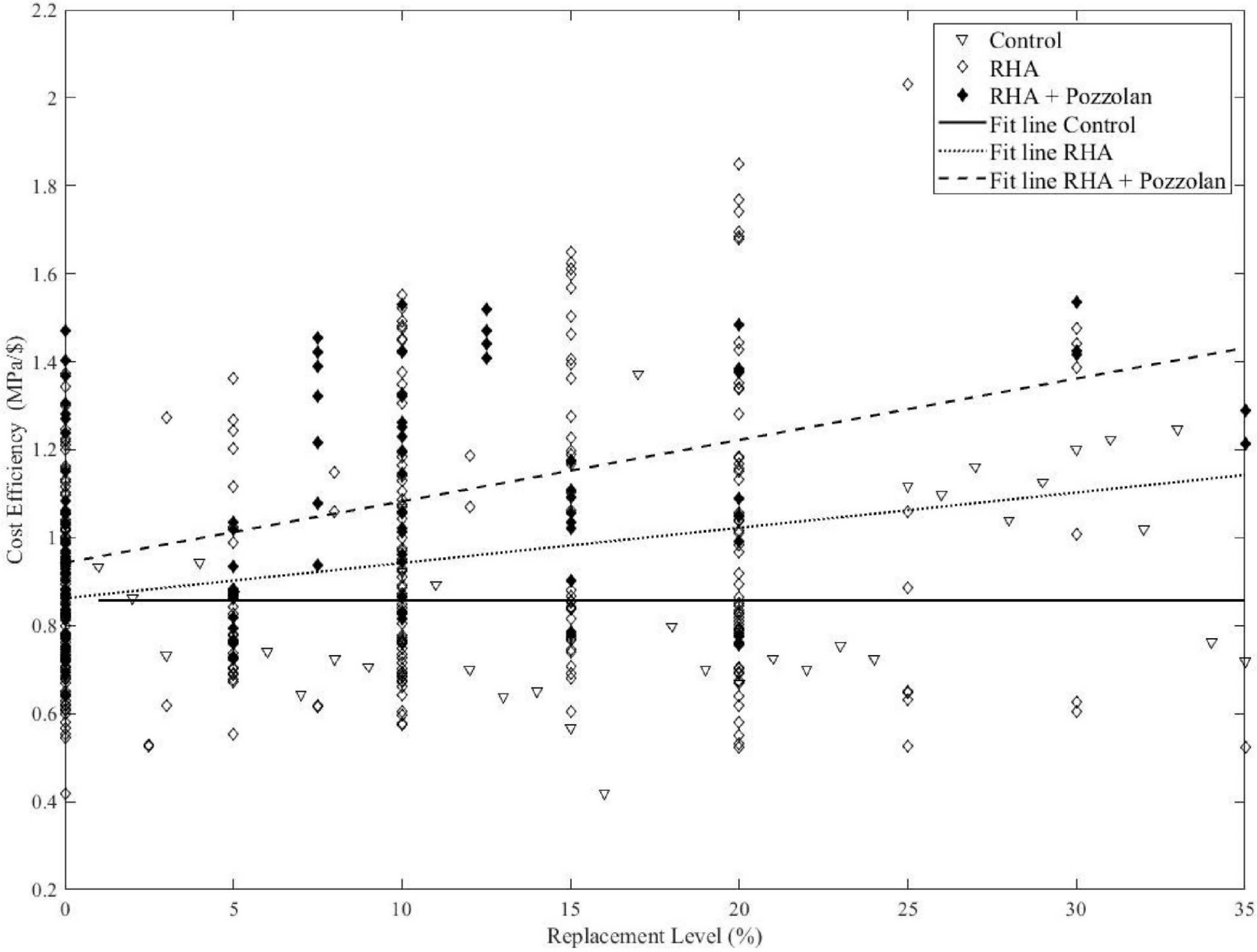
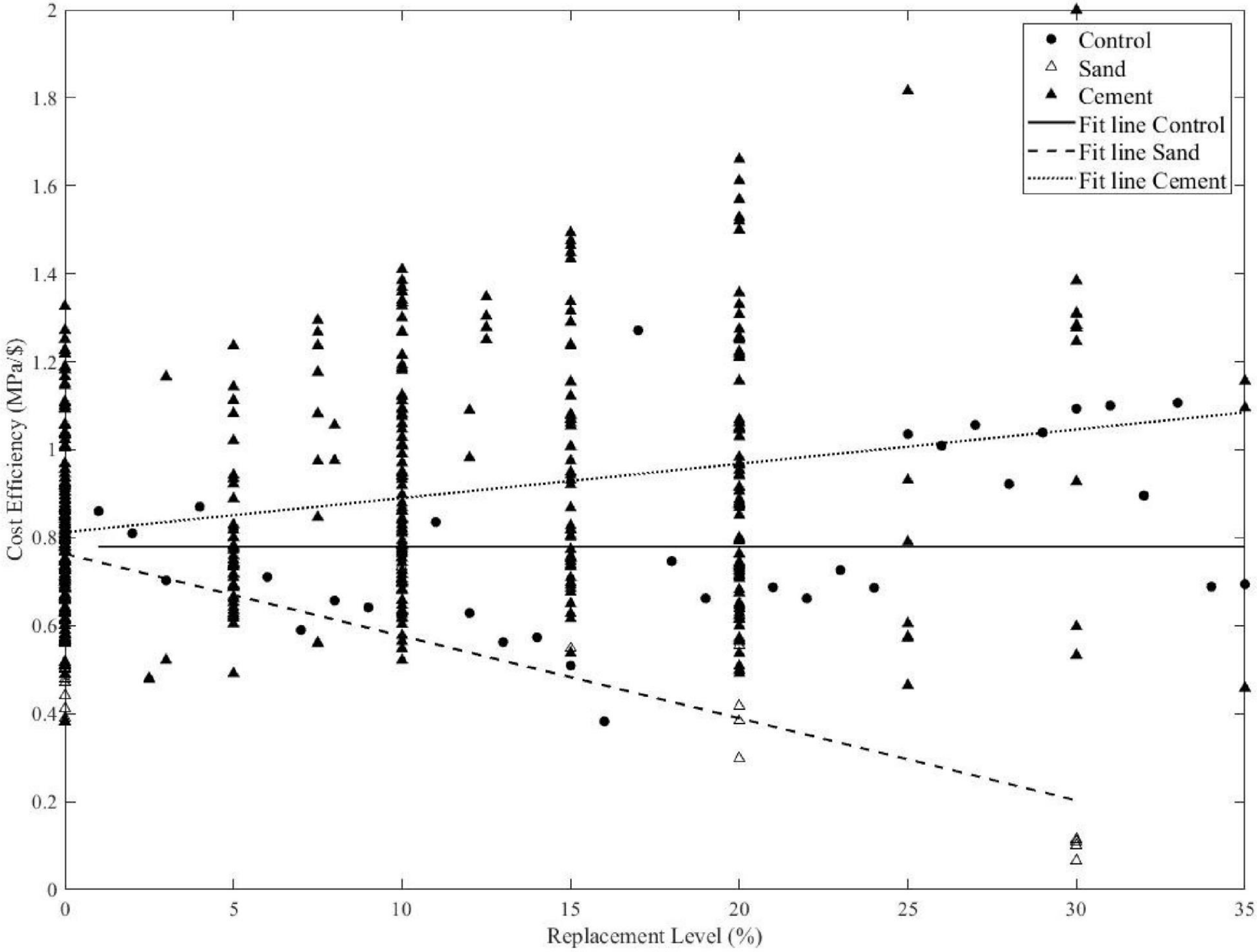
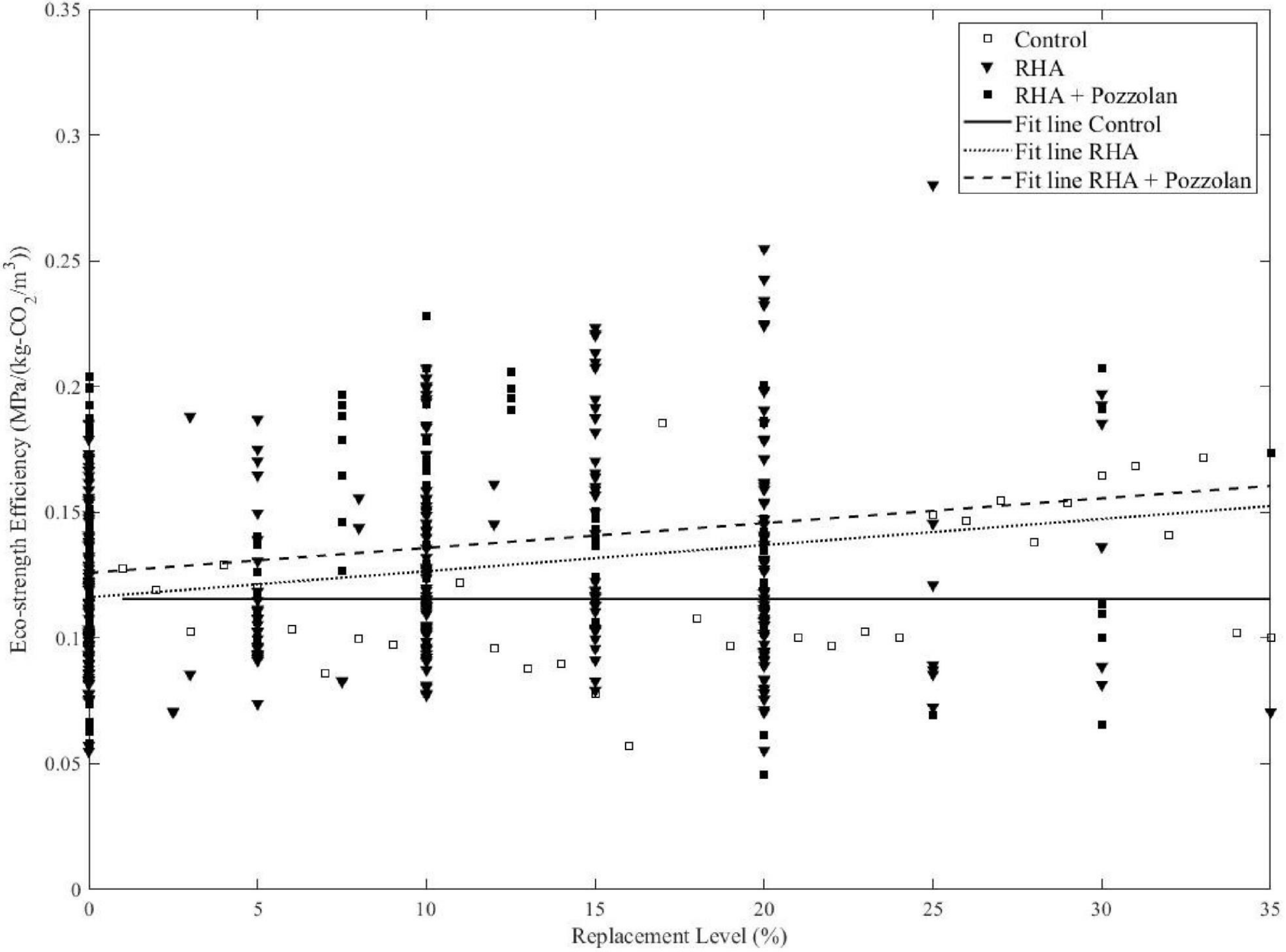



Cost Efficiency (MPa/$)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Replacement Level (%)
0
5
10
15
20
25
30
35
● Control
△ Sand
▲ Cement
Fit line Control
Fit line Sand
Fit line Cement


Eco-strength Efficiency (MPa/(kg-CO$_2$/m^3))
Replacement Level (%)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
5
10
15
20
25
30
35
Control
RHA
RHA + Pozzolan
Fit line Control
Fit line RHA
Fit line RHA + Pozzolan

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