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Bringing Ceramic Recycling into Circular Economy in Egypt for Concrete Structural Elements

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Abstract:
Background: *Worldwide the demand of concrete production is usually increase according to augmentation of construction purposes in developing countries. Therefore, it is important to explore the potential of such waste material, especially when locally available for concrete production.*
Materials and Methods: *Recycling the ceramic waste offers a win - win solution, where it reduces the generated ceramic waste, as well as conserve the natural aggregate by replaced percentage of uncontaminated ceramic waste. These expected sustainable benefits were the motivation to this research to examine the technical and managerial feasibility of recycling ceramic waste for construction building using PESTLE technique. Thus, this research has promoted the principles of circular economy to turn it into applicable practice in construction building. This research has examined the bending and shear behavior of reinforced concrete beams made with different ratios of ceramic waste substitution varied from 0% to 80% replacement of natural aggregates.*
Results: *The experimental results indicated the feasibility of employing ceramic waste to replace part up to 40% of the natural coarse aggregate in structural concrete elements.*
Conclusion: *This research proves the profitable shift to circular economy for Manufactures / Generators and the construction market (Designer, Supplier, and Operator).*

Key Words: *Construction and Demolition Waste, Circular Economy, Ceramic Waste, Recycled Coarse Aggregate for Structural Elements.*

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I. Introduction

Construction industry and related products has a boom growth nowadays. Construction industry represents about 6.4% of GDP in Egypt in 2019. Although it contributes positively for improving the quality of life and well-being for citizens, it also has negative environmental and economic impacts as a result of the generated waste during project's life cycle. Therefore, the Construction and Demolition Waste (C&D waste) management has become a crucial need to reduce the accumulated or dumped waste , as well as reducing the consumption of the natural raw material. 3R strategies (Reduce, Reuse, and Recycle) are the main strategies for leading the C&D waste management processes. Ceramic and anti- melting material manufacturing represent about 7% of the production value in Egyptian Industrial sectors (EEAA, 2020). According to Egyptian Environmental Affairs Agency, the defected products after firing (tiles floor) is considered as one of main generated solid waste of ceramic industry (EEAA, 2020). Reuse offers benefits in terms of energy; especially when the waste is from kiln industries (the ceramics industry). Where, highly endothermic decomposition reactions have already taken place, thus recovering the previously incorporated energy during production will be significant benefit (Juanet al.,2010).

The increased quantities of the generated industrial and / or construction and demolition waste are becoming severe problem. Consequently, there is a crucial need to find innovative solutions to apply the sustainable management for managing the industrial waste and C&D waste in order to alleviate the negative environmental, economic, and social impacts. Recycled aggregates, as other alternative materials, represent an environmentally friendly solution to reduce the amount of waste disposed in landfill (Collivignarelli et al., 2020). Recycling of the crushed / defected ceramic tiles will maximize the economic and energy benefits, as well as it will alleviate the exhaustion of Virgin raw material (coarse aggregate). This ceramic waste will be recycled to be crushed and procure directly from the generator (manufactory) to the user (construction project), which will secure a privilege utilization of an uncontaminated waste. Therefore, this research will focus on discussing the feasibility of recycling the ceramic waste as coarse aggregate in structural concrete elements.

From an economic point of view, there is no better construction material like concrete. According to Struble and Godfrey (2006) and Rahal (2007) , the production of the concrete beam required less energy and had a lower net environmental impact than production of the steel I-beam designed for the same engineering function. On the other hand, the global world concrete construction industry needs a huge amount of natural aggregate is about 10 billion tons per year. While the content of coarse aggregate in concrete mix is about 60-80% amount of total aggregate. Consequently, the concept of reserving the natural resources is preferable to replace the natural aggregates with recycled aggregates.

Ceramic industry is the major source of uncontaminated ceramic waste on the contrary the generated ceramic waste from construction and demolition buildings that may be mixed with other material such as mortar or gypsum. In ceramic industry, a significant part of ceramic waste is not recycled in the production process; however, it is automatically separated. While, in construction and demolition works, it is needed to be separated and be cleaned **(**Correia et al., 2006).

Circular Economy of Ceramic Waste:

About 3% of production volume of ceramic is the waste of ceramic industry that is generated during processing and transport (From interviews). This industry remains under great pressure to find effective recycling methods for its waste and by-products (Klimeket al., 2020)**.**There is a broad range of sustainableapplications to reuse ceramic waste; such as land leveling, landscaping, road pavement, reuse in new constructions, filling mortars, and coating mortars (Correia et al. , 2006).

Aggregates are one of the components to be substitute in concrete mix design. The most common fine aggregates in reinforced concrete (RC) are sand or crushed stone. Coarse aggregates play a role in determining the final strength of concrete composite. The increasing demand of such components for the concrete industry is depleting natural resources, so alternative solutions should be created to substitute them in the production process.

The integration of recycled ceramic waste and by-products in concrete is a sustainable alternative for the disposal of such materials, generally directed to landfills or incinerators. Recycled aggregates are another relevant option, embodying a possible closed-loop circular economy example in the building sector.

Circular Economy is supporting the concept of life cycle thinking, where it is defined as an economic system that is based on business models which replace the “end-of-life” concept to a stage of any product at the end of its useful life by introducing these materials / products into another life cycle through reuse, recovery and recycling. (Ginga et al., 2020; Almeida et al., 2016). This concept leads to resource conservations, and promote energy efficiency that consequently significantly reduce the environmental degradation while contributing to economic growth and creating new markets, where there is no waste and the resources are managed sustainably.

Ceramic industry have invested in innovative alternatives for transition towards circular economy such as: reuse of defected ceramic tiles as roof tiles, external landscape, or to be recycled as crushed aggregate for different construction applications. Construction and metallurgical industry categories are the main sources for alternative materials for both the components, with ceramic and lead slag reaching a full replacement for both fine and coarse aggregates (Collivignarelli et al., 2020). Recycled ceramic aggregate has a positive impact on strength parameters of mortars with concurrent reduction in absorbability and capillary action. Testing of mortar with the addition of ceramic aggregate has proved better frost resistance and resistance to salt crystallization as than that of mortar to which sand had been added. (Klimek et. al., 2020)**.**

By comparing the durability of mix contained recycled ceramic aggregate against the traditional mix; it was found that the resistance to chloride-ionpenetration is decreased as the recycled aggregate content increased, even if it still fit in low- very low corrosion risk level. Except for water permeability, even oxygen permeability and chloride diffusion performances have shown better results (Collivignarelli et al., 2020; Ma et al., 2019).

Physical and Mechanical Performance of Ceramic Waste as Recycled Coarse Aggregate:

According to Medina et al. (2009), conducted a research on the use of ceramic waste as a partial substitution of coarse aggregates in concrete from 15% up to 25%and produced a positive results. The increase in partial substitution of coarse aggregates in concrete resulted in lower density in concrete, and higher compressive and tensile strength. The concrete produced was suitable for structural use. Zimbili et al. (2014) indicated that, ceramic waste is suitable for usage in both structural and non-structural concrete and even for mortars. This mix showed better performance than normal concrete, in properties such as density, durability, permeability and compressive strength. Ikponmwosa and Ehikhuenmen (2018) have studied the flexural performance of unreinforced and reinforced concrete beams with ceramic waste as replacement of coarse aggregate. The investigation showed an optimum allowable deflection value is 5.09mm at 25% replacement level. They concluded that the use of ceramic waste in concrete is sustainable for low-cost housing projects. Paul Awoyera et al (2018) studied the use of ceramic wastes as partial replacement of natural aggregates in concrete.

The effect of both curing mode and high temperature were evaluated. It was deducted that ceramic-laterised concrete develops appreciable strength under polythene covering curing method, but the reference concrete developed higher compressive strength under water immersion curing method. The ceramic-laterised concrete performs better than normal concrete at elevated temperature

Ceramic waste as raw material for structural elements:

Pacheco Torgal et al. (2011) examined the feasibility of using ceramic wastes in concrete. Results show that concrete with 20% ceramic powder as cement replacement although it has minor strength loss possess increase durability performance. Results also show that the concrete mixtures with 20% ceramic coarse aggregates perform better than control concrete mixtures concerning compressive strength and durability performance. Andrzej Lapko and Robert Grygo (2014) made an experimental study on the behavior of large-scale RC beams made totally from coarse recycled aggregate. The results revealed shape of failure and critical values of loading forces being similar to control beams made of natural aggregates, however the deformability parameters (deflections, concrete strain and cracking width) in the two types of tested beams were different. The results confirmed the possibility of using recycled aggregates for production of good quality concrete used for structural elements like RC beams or slabs, what is very important for the needs of environment protection.

II. Materials and Methods

Research Objectives and Methodology:

The main objective of this research is examining the applicability and feasibility of using uncontaminated ceramic waste as a recycled coarse aggregate through a technical and managerial study of structural concrete building elements. This objective is attained by achieving the following goals:

1) Managerial Feasibility: exploring the viability of recycling ceramic waste in construction building, by conduction PESTLE analysis.
2) Technical Feasibility: Examining the optimum replacement percentage of ceramic waste as recycled coarse aggregate to the structural concrete element, through studying the behavior of reinforced concrete beams under shear and flexural stresses.

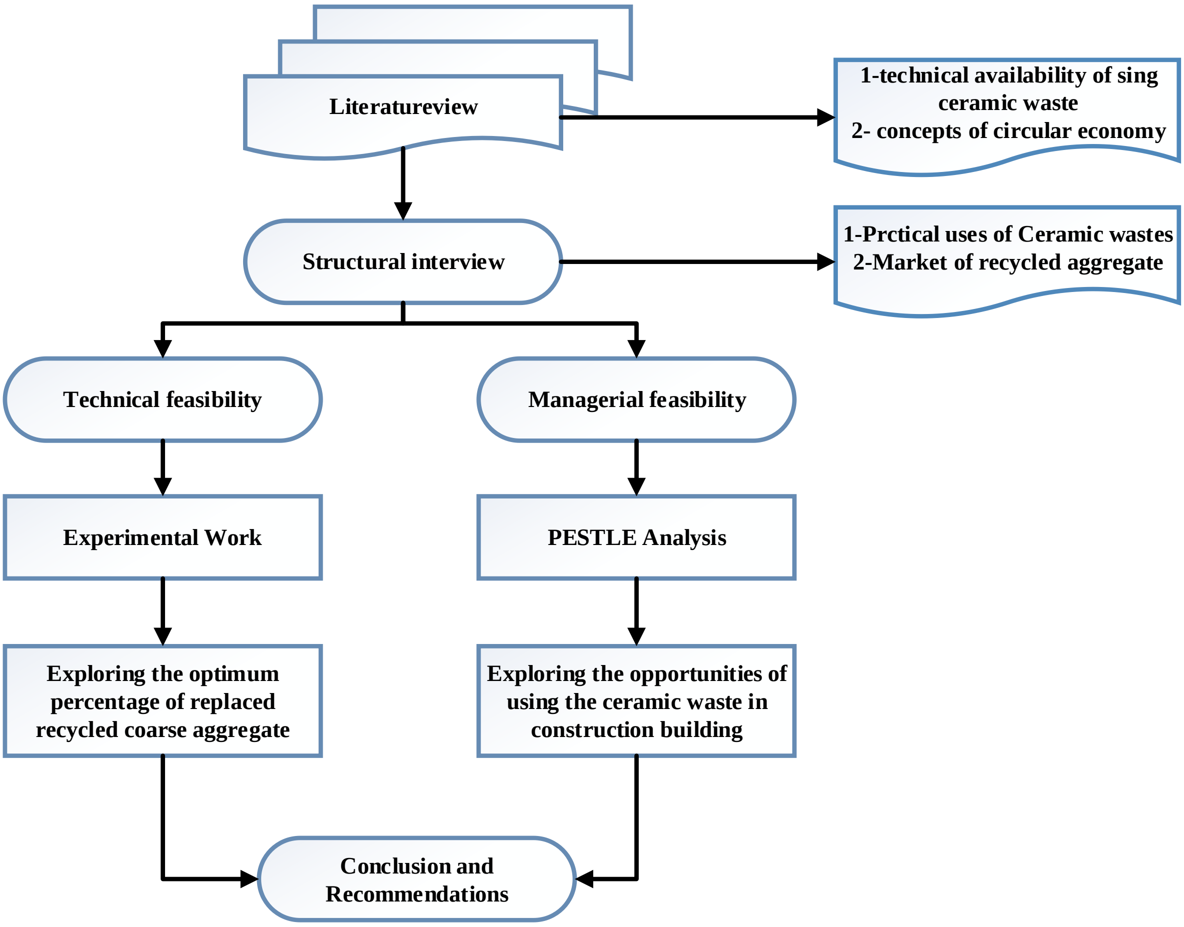

Fig.(1) : Research Methodology

A comprehensive literature is conducted to cover the concepts of PESTLE analysis (Political, Economic, Social, Technological, Legal, and Environmental). The literature has also reviewed the previous studies of using ceramic waste and experiments for replacing the natural coarse aggregate by the recycled aggregate. Then a structured interview with five of experts in largest ceramic factories in Egypt. These interviews have investigated the current uses of ceramic waste in Egypt and explored its benefits in context of capabilities and opportunities in Egyptian market. In parallel, the experimental work is conducted to examine the behavior of reinforced concrete beams under shear and flexural stresses. As well as the performing of the PESTLE analysis. Figure (1) draws these steps of methodology to start with literature and end by the conclusion.

Experimental program:

The experimental program is aiming to explore the optimum replacement percentage of recycled aggregate in structural beams to substitute the coarse aggregate. Therefore , The experimental program is conducted at the reinforced concrete laboratory at the “Housing and Building National research center” in Giza, it consisted of ten reinforced concrete beams divided into two groups; one to investigate the flexural behavior that was denoted by (F), and the other for studying shear behavior that was denote with (S). The replacement ceramic waste used as coarse aggregates in beams varied from 0% to 80% with an incremental ratio 20%. Beams without ceramic waste is considered as control sample. Each beam was designed with dimension 150*250*2000mm that has been reinforced with 12mm diameter as bottom reinforcement and 10mm diameter as top reinforcement both are deformed high grade steel as shown in Fig. (2).

Fig.(2-a): Reinforcement detail for flexure **Fig.(2-b):** Reinforcement detail for shear

Fig.2: The detail of reinforcement

▪ **Material and Mix Design**

The experimental program targets to investigate the influence of using recycled ceramic as partial replacement for natural coarse aggregates on the behavior of reinforced concrete beams under both shear and flexural stresses. The experiment tools were depicted in Fig. (3 a,b,c). Firstly, ceramic tiles were collected with the same properties to ensure the uniformity. Hence, the tiles were crushed using automatic crusher as illustrated in Fig. (3-a) with maximum size 10 mm to partially replace the coarse aggregates in concrete mix as shown in Fig. (3-b). Five concrete mixtures were designed to achieve average compressive strength 25 MPa as shown in Table (1). Where the replacement ratio started from zero to 80% with incremental increasing 20%. The results of slump test in table (1) shows that by increasing the ratio of replacement the ceramic waste aggregates the fresh concrete collapsed too wet with some aggregates segregation, as the water absorption of ceramic aggregates is lower than natural aggregates.

Table (1): Concrete Mix Design:

Mix NO.	**Specimen ID**	**Cement (kg)**	**Sand (kg)**	**Natural Coarse aggregate (kg)**	**ceramic waste coarse aggregate (kg)**	**Water (kg)**	**Slump test (mm)**
Mix 1	F0,S0	350	730	1090	Zero	190	120
Mix 2	F20,S20	350	730	872	218	190	140
Mix 3	F40,S40	350	730	654	436	190	150
Mix 4	F60,S60	350	730	436	654	190	180
Mix 5	F80,S80	350	730	218	872	190	200

Fig. 3-a: automatic crusher **Fig. (3-b):** crushed ceramic waste **Fig.(3-c):** Slump test

Fig.(3): Experiment tools : Automatic crusher , Crushed Ceramic waste and Slump test

- **Specimen Fabrication**

Coarse and fine natural aggregates were placed in the mixing drum to be mixed for one minute at first. Then the cement was added and ceramic aggregates. Finally, adding water, and keep mixing for two to three minutes. The concrete was placed in the wooden form and vibrated, then the concrete surface was finished. The reinforced concrete beams were treated for28 days under laboratory conditions

- **Experimental procedure**

The beams were simply supported at the ends on a two rigid steel supports. The beams were subjected to third-point loading applied through a spreader beam that formed part of the loading system. The two-point load applied with spacing 400mm as demonstrated in Fig. (4a) to produce a constant moment in the central span of beams which tested under flexural. While the two-point applied load with spacing 800mm for beams under shear stresses as shown in Fig.(4b). The load was gradually increased up to failure. The deflections were measured at the first and middle third of the span using linear variable transducer (LVDT). The measured data were recorded by data logger connected with computer system program using “lab view” software.

Fig. (4-a): Test set-up - Flexure **Fig. (4-b):** Test set-up- Shear

Fig. (4): Test set-up

III. Results& Analysis

- **Failure mode and crack pattern**

The crack configuration for specimens which designed to fail in flexure mode were showed a typical crack pattern as planning to be collapsed in flexure with brittle mode for all ratios of replacement. While load increase; cracks started to appear in the bottom chord of the beam within the middle third of the beam then extended vertically to the compression zone (top chord).Cracks became wider by load increase up to failure with sudden drop of load as clarified in Fig.(5a). For beams failed in shear the cracks appeared at support and propagated diagonally about two-third of the depth of the beams from tension face (bottom), then, extending towards the compression zone of the beams (top). Thereafter, the propagation was gradual and the cracks widened until failure occurred such as shown in Fig. (5b).

Fig.(5-a): crack pattern- Flexure

Fig.(5-b): crack pattern- Shear

Fig.(5): crack pattern

- **Load- Deflection relationships**

Load-mid span deflections for tested beams have shown in Fig.(6a). Generally, for beams failed in flexure (Group 1) there is a small difference in deflections between beams for each level of loading force along loading time. Whereas at failure the deflections in beam with natural aggregates (F0) and beam with 80 % of ceramic waste (F80) were greater than those of 20% and 40% ceramic waste replacement (F20, F40). While the beam with 60% ceramic replacement (F60) has the minimum deflection at failure. For specimens collapsed shear (Group2), along the loading time up to failure, the maximum deflection was for the beams made with natural aggregates (S0). However, beams with ratio of ceramic replacement 60 %and 80% (S60, S80) have greater, deflections compared with those of 20%and 40% replacement of ceramic waste (S20,S40) as in Fig.(6b).

Figures (7a, 7b) illustrates the load-steel strain curves, which show the compatibility of the concrete, and reinforcement causes them to deform together. The steel yielding stage occurred after appearing of cracks either flexural or shear cracks.

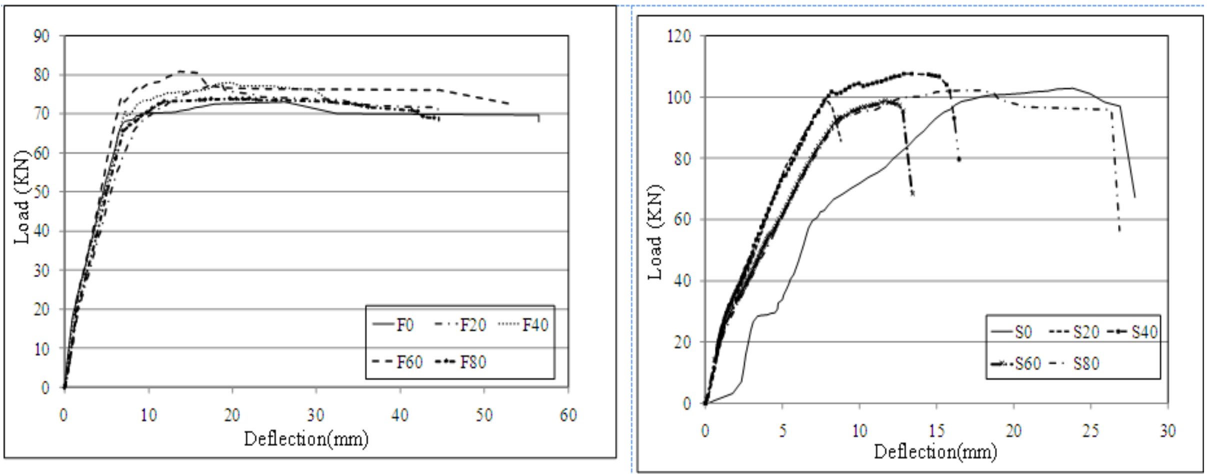

Fig.(6 -a): Load-deflection relationship - Flexure

Fig.(6 -b): Load-deflection relationship- Shear

Fig.(6): Load-deflection relationship

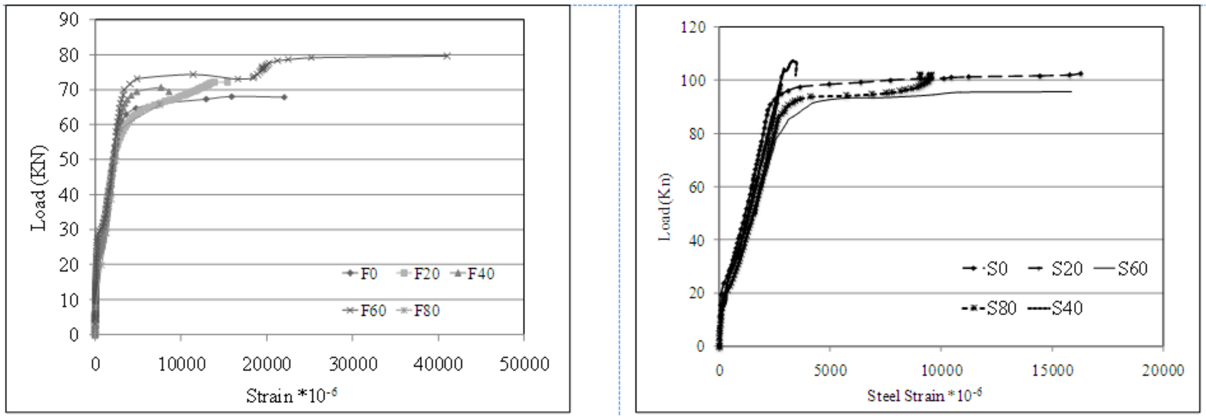

Fig.(7- a): Load-Steel strain relationship – Flexure

Fig.(7 -b): Load-steel strain relationship - Shear

Fig.(7): Load-steal strain relationship

Table (2) shows that there is a slightly increase in concrete compressive strength in 20% replacement of ceramic waste comparing with the control mix. Then, the maximum compressive strength achieved at 40% of ceramic replacement. After that, the compressive strength tends to diminution at 60 % and 80% of waste ceramic substitution.

Looking at the two groups; according to the flexure test and shearing test separately, it was found that in flexure test F40 and F60 gives the best results for ductility factor and maximum load, respectively. As for the shearing test, S40 gives better results for both ductility factor and maximum load with a great difference than other replacement ratios.

The ductility factor indicates that the specimens F40 and S40 have the greater value than the other value of replacement compared with control beam.

- **Effect of ceramic waste aggregates on flexure and shear capacity**

The influence of ceramic waste on the flexure and shearing strength were presented in Table (3). The change in the ceramic substitution ratios led to a variable change in moment and shear stress, it was found that 40% replacement ratio had better results compared to the control sample and other ratios of substitution. This can be attributed to the reduction in density of the concrete with the increase in flaky aggregates and smooth surface texture of ceramic wastes which could resulted in poor bonding properties in the concrete mix. Also, the water absorption of the ceramic aggregates were less than by about 40% of the natural aggregates which lead to weakness of bond between aggregates and cement past. Consequently, lower bond between concrete matrix and steel bar reinforcement, so the increase in coarse ceramic aggregates replacement more than 40% leads to reduce the maximum capacity of the beam as illustrated in Fig.(8).

Table (2): Test results

Group	Beam ID	F_{cu} at 28 day (Mpa)	cracking load (Kn)	Maximum Load (kn)	Deflection at failure (mm)	Deflection at yield (mm)	Ductility factor
Group 1	F0	20.02	19.2	73	26.24	13.13	2.00
	F20	21.34	23.4	77.6	18.78	7.33	2.56
	F40	**23.15**	26.4	**77.9**	19.98	7.05	**2.83**
	F60	20.79	17.6	**80.7**	13.71	6.44	**2.13**
	F80	19.43	19.8	74	22.02	11.88	1.85
Group 2	S0	20.02	19.7	102.8	23.82	15.43	1.54
	S20	21.34	25.9	98.6	7.94	7.61	1.04
	S40	**23.15**	26.8	**107.5**	13.40	7.3	**1.84**
	S60	20.79	25.5	98.2	11.69	7.84	1.49
	S80	19.43	19.5	102	17.45	12.94	1.35

Table (3): Experimental and theoretical bending moment and shear stress

Group	Beam ID	Experimental Moment (kn.m)	Theoretical Moment (Kn.m)
Group1	F0	25.55	16.79
	F20	27.16	16.76
	F40	**27.265**	**16.83**
	F60	28.245	16.74
	F80	25.9	16.67
Group2	**Beam ID**	**Experimental shear stress (MPa)**	**Theoretical Shear stress (MPa)**
	S0	1.49	1.34
	S20	1.44	1.35
	S40	**1.57**	**1.37**
	S60	1.44	1.35
	S80	1.48	1.33

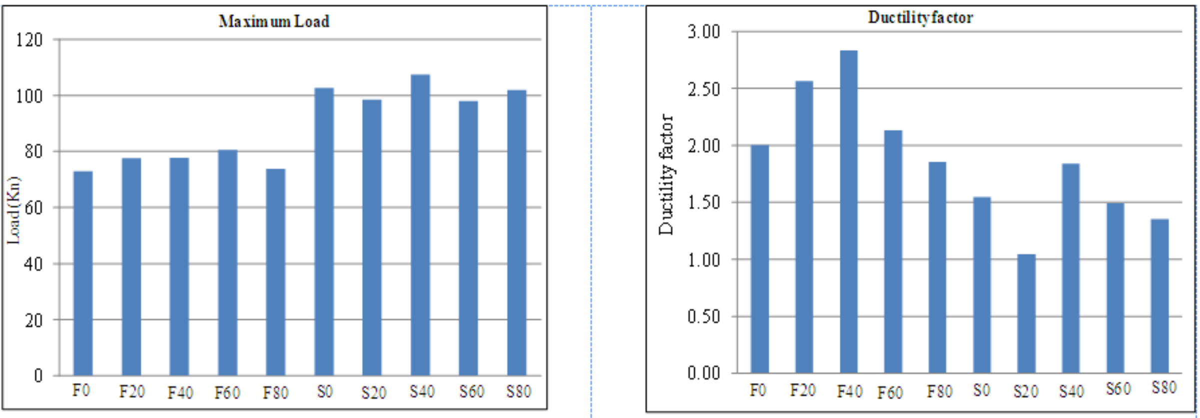

Fig (8): Maximum Load and ductility factor

IV. Discussion

PESTLE Analysis: The technical feasibility of using the ceramic recycled aggregate is proved through flexure and shear analysis. In parallel, the managerial feasibility is conducted using PESTLE Analysis to determine its potential of success and the viability of solution before commencing. PESTLE Analysis is applied to identify the Political, Economic, Social, Technological, Legal and Environmental factors that have a positive or negative impact on the successful implementation of a project / system (Christodoulou and Cullinane , 2019). PESTLE technique was utilized by different researches as a powerful approach for the development of reliable future scenarios, effective business models, and strategic tool for decision making (Attia , 2020 ;Turkyilmaz et al. , 2019).

The perceived items of of PESTLE analysis have been extracted based on three sources: 1) literature review (Attia , 2020 ;Turkyilmaz et al. , 2019) , 2) experts' opinion that have been extracted through interview , where the existing current practices and uses of ceramic waste, and the current opportunities and challenges , and 3) the governmental initiatives through issued legislations and technical guidelines . Table (4) summarizes the items of PESTLE analysis for practices of recycling ceramic waste as coarse aggregate for construction building. It identifies how the dimensions of PESTLE analysis affect the circular economy of ceramic waste either positively or negatively.

The PESTLE analysis shows that the positive impacts are the dominant impacts more than the negative ones. This analysis is supporting proofs of the viability of using the ceramic waste as recycled aggregate for construction buildings.

Table (4): PESTLE Analysis for PESTLE analysis for practices of recycling ceramic waste as coarse aggregate for construction building

PESTLE's Dimensions	**Items**	**Impact**
Political	– National Strategy for C&D Waste Management in Egypt has been developed and approved by Ministry of Environment in 2020. – Egypt Vision 2030 is adopted by most governmental sectors that consider the sustainable practices in most of planned projects. – Waste Management Regulatory Authority (WMRA) - Ministry of Environment, is established to regulate and oversee the waste management processes. Also , to attract and promote investments in process of waste management : (collection ,transportation , ..., recycling) http://www.wmra.gov.eg/en-s/AboutUs/Pages/Mission.aspx	Positive
Economic	– The ceramic manufactory already has the required resources and capabilities (crushers, laboratory,..) for recycling the defected ceramic tiles as ceramic waste to convert it to recycled coarse aggregate .i.e: there is no extra investment cost .	Positive
	– The manufactory will sell the ceramic waste as a recycled aggregate (as a product) , not as a waste ; which will secure better price and benefit.	Positive
	– The user / customer will buy a non-contaminated product, which has been produced, tested and accredited according to the related Egyptian codes and standards.	Positive
	– There is a market need, where there is a lack in construction materials and products manufactured from recycled materials in Egypt, which represent an opportunity to be one of pioneers in this new market.	Positive
	– There is no specified financial incentives for investors/ generators to establish recycling units in their factories.	Negative
	– Low expectations for sales of recycled construction materials in Egypt due to Negative consumer perception for recycled aggregates.	Negative
Social	– Conservative culture towards using the recycled aggregate may discourage using recycled construction products. – Up to now, there is no governmental initiatives for green procurement that will foster buying the recycled construction products.	Negative
Technological	– Availability of technical knowledge he required equipment for crushing and recycling by using the existing required equipment for recycling the ceramic waste as part of factory's assets, there is no significant training is needed. – Technology and expertise for recycling C&D waste, and ceramic waste are available in Egypt at the experimental research and pilot implementation levels. – The availability of issued Egyptian technical guides, codes, and standards: (Egyptian code for recycling C&D WASTE in construction, HBRC, 2017) , (1109/2021- Egyptian standard of Aggregates for concrete, EOS , 2021). – These technical specifications will pave the way for governmental initiatives for green procurement that will foster the market of accredited recycled products.	Positive
Legal	– Egypt has issued a new legislation to regulate all activities related to solid waste management and disposal fees including C&D waste (law No. 202 -2020). – Egyptian Organization for Standards & Quality (EOS) has modified 16 of The Egyptian standard specifications that consider recycled C&D waste as an accepted source of materials for Construction materials/products.	Positive
Environmental	– Reducing extraction of raw materials, which avoid production of dust, save the natural resources and reduce the embodied energy of extraction and transportation of raw materials. – Allowing better usage of land (instead of using it as landfill space), especially with Land scarcity. – Current practices in Egypt of illegal dumping of C&D waste and industrial waste is considered a threat to the environment due to dust and possible hazardous. On other side, it is considered as motivation to implement the viable solutions to reduce the environmental problems and contaminations facing Egyptian cities.	Positive

V. Conclusion and Study Limits

In light of the aggravation of the accumulated C&D waste problem, and the necessity to preserve the natural resources to meet the future needs, this research has found the crucial need to extract a viable technical and managerial solution. The developed solution was to recycle the ceramic waste to partially substitute the natural aggregate in concrete structural elements (beams); as transition to circular economy. This paper has proved the technical and managerial feasibility through applying experimental work and PESTLE analysis, where the positive impacts has superfat the negative impacts for six dimensions of PESTLE analysis. As well as, the technical experiments have revealed that the optimum substituted percentage of ceramic recycled aggregate is not more than 40% based on analyzing the flexure and shear stress.

The following conclusions have been derived and listed as following:

1- The failure mode for reinforced concrete beams were typical cracks propagation either beam subjected to flexure or shear stresses irrespective of ceramic waste content.
2- Lesser failure load was attained with increase the ceramic waste content in concrete mix.
3- The ductility index is influenced by changes of replacement ratio.
4- It is found that the optimum allowable ratio of substitution is not more than 40% of ceramic waste replacement.

These results contribute paving the way to encourage the investment in the field of recycling C&D waste, especially the ceramic waste to produce the non-contaminated recycled aggregate. This solution has achieved the win-win solution for both of the generator / investor and the consumer / user / supplier.

This research is limited to using the defected ceramic tiles (directly from the ceramic factory), where the ceramic waste is free from contamination; as the main distinction and strength point of using ceramic waste in structural elements, which comply with the conservative construction practices. .

RECOMMENDATION AND FUTURE STUDY:

It is recommended to start up recycling units in ceramic factories, where its product will be the recycled coarse aggregate, especially the factory has the required capabilities and resources. This recommendation is based on the conducted PESTLE analysis that clarified the Mutual benefit for both of the generator and customer. As a future study, this research recommend studying the optimized business model, as well as identifying the drivers and challenges for recycling ceramic waste in construction buildings and roads; based on case study.

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