PAPER 8

EXPERIMENTAL EVALUATION OF FLY ASH AND STEEL DUST FOR ECO-FRIENDLY MORTARS IN LOW-COST HOUSING IN SOUTH AFRICA

Vhuhwavho Pertunia Mudau[1], Marinus Smit[2]
[1,2]Department of Civil Engineering, Faculty of Engineering and Technology, Vaal

ABSTRACT

The ever-increasing backlog of applications of government low-cost housing in South Africa has been a long-standing socio-economic challenge as presented in Figure 1. The use of mortar is extremely important in masonry structures because mortar serves as the binding agent that holds bricks together and distributes loads in the structure. The increased price of mortar, primarily due to the increase in cement prices, has been a major hindrance to the construction of low-cost housing in South Africa. Furthermore, the elevated carbon emission associated with cement production which is one of the key ingredients in masonry production has prompted for the search of an alternative cement replacement.

The present study analyses the mechanical properties of mortars with the use of fly ash and steel dust (FASD) as partial replacements of cement in 5%, 10% and 15% proportions. The reason is based on two-fold nature of the problem minimisation of the cost of house building in South Africa and the utilisation of waste materials for the benefit of the environment. Specimens of the mortar were manufactured and studied for density, compressive strength and flexural strength after 7 and 28 days. The outcomes demonstrate that the density of the specimen increases proportionally with the FASD content varying within the range of ~2240-2300 kg/m^3 in control sample and ~2550-2600 kg/m^3 in 15% replacement proportion. The maximal value of compressive strength was obtained at 10% replacement of cement with FASD and exceeded control sample and other proportions; the flexural strength increased up to 15% replacement and reached ~10.5 MPa after 28 days. Incorporating FASD in mortar as a partial cement replacement greatly improved its density, compressive strength, and flexural strength.

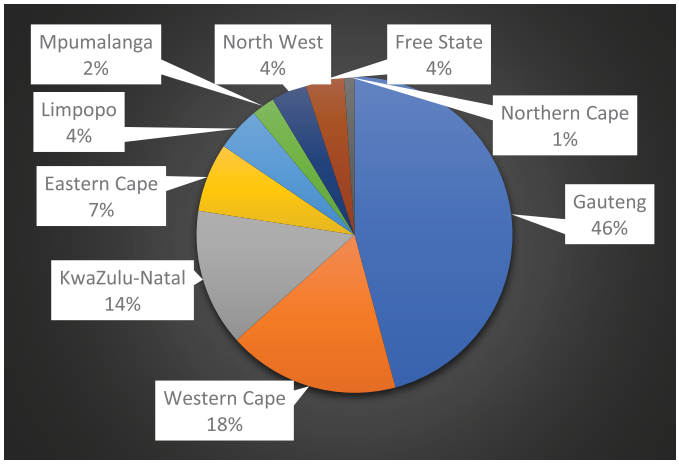


FIGURE 1: *Housing Need by Province*

1. INTRODUCTION

Housing is a basic human right and an essential criterion of socio-economic development and poverty alleviation. In South Africa, the government initiated the Reconstruction and Development Programme (RDP), aiming to enhance the living standards by provision of low-cost housing to poor people (Akinsulire et al., 2024). Even though such a measure was taken, there still exists a serious backlog of housing due to rapid population growth, inequality, and high cost of building materials (Ngema et al., 2025). The high cost of masonry materials, especially cement mortar, is a major factor hampering delivery of low-cost housing.

Mortar is an integral part of masonry construction since it ensures bonding of brickwork and blockwork, load transfer, strength, durability, and serviceability of structures (Arulmoly et al., 2021). Traditional mortar composition mainly includes cement, sand, and water. Cement is a principal binding component while sand provides volume and dimensions (Ludick et al., 2021; Madisha & Khumalo, 2021). However, cement is the most expensive ingredient of mortar, and the production process accounts for approximately 6-8% of all carbon dioxide emissions worldwide (Bărbulescu & Hosen, 2025). Therefore, the use of supplementary cementitious materials can help decrease cement content and thus reduce costs and impacts on the environment.

By-products of industries have been receiving a lot of focus in terms of being sustainable substitutes to traditional cementitious materials. It has been established that materials such as blast furnace slag, fly ash, silica fume, and metakaolin improve the performance of mechanical characteristics while lowering the carbon footprint of cement-based materials via secondary hydration reactions and matrix densification (Hamada et al., 2023; Jabba, 2023). Dobiszewska (2023) found out that substituting cement with rock dust at levels up to 10–15% does not negatively impact mortar characteristics, while Rajput (2018) noted an increase in compressive strength of 13.1% and 8.1% in M20 and M30 concrete, respectively, upon the full replacement of natural sand with crushed stone dust. Mohammed and Al-Numan (2024) noted an increase of 4.5% in 56-day compressive strength from adding lime powder. This proves the suitability of industrial by-products as sustainable substitutes.

Despite their huge production volumes, there are still many industrial waste types that are poorly used. For instance, stockpiles of fly ash take up large land areas and present an environmental hazard by releasing dust into the air, contaminating the water resources, and posing rehabilitation risks. In a similar fashion, the byproduct of steel production known as steel dust is often deposited on landfills, thus raising the problem of its disposal

TABLE 1: *Key chemical compositions (wt%)*

Samples	Chemical composition (wt%)														
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	H_2O^-	K_2O	P_2O_5	Cr_2O_3	SO_3	Na_2O	LOI	Total
Steel dust	1.15	0.15	5.65	70.52	2.45	8.98	5.78	-	0.98	0.23	-	-	0.67	3.47	100.01
Fly ash	19.514	0.442	8.121	3.216	0.048	1.767	28.856	-0.037	1.098	5.876	0.010	2.444	0.845	27.17	99.388
OPC cement	20.25	-	5.61	3.99	-	2.63	62.68	-	0.8	-	-	2.73	0.18	2.88	101.75

and possible contamination. Although fly ash has been studied extensively as an additive to cementitious materials, a combination of fly ash and steel dust as additives to cement at various percentages of cement replacement in mortars has not been explored yet.

For this reason, the current research seeks to explore the mechanical behaviour of cement-sand mortars, where fly ash and steel dust from an electric arc furnace (FASD) have been used as cement replacement materials in proportions of 0%, 5%, 10% and 15%. This research is conducted with the intention of assessing the possibility of using such industrial wastes for making sustainable and economically viable mortar for affordable housing applications.

2. METHODOLOGY

2.1 Materials used

Mortar was formulated using sand, steel dust, fly ash, and tap water. Steel dust which is an industrial by-product was procured from a steel manufacturing company in Gauteng, South Africa. As a base for comparison, a control mixture was also made using Ordinary Portland cement, sand, and tap water. The control sample provided a basis upon which the results produced by adding, steel dust, and legacy ash could be compared. The dry samples including fly ash, steel dust, and sand samples were oven-dried at 100 ± 5°C to have better control of their moisture content and eliminate any variation caused by free water. The partial replacement of cement with fly ash and steel dust also reduced the overall content of cement.

TABLE 2: *Physical properties of samples*

Materials	Specific gravity
Ordinary Portland cement	3.10
Fly ash	2.77
Steel dust	3.50
Natural sand	2.60

TABLE 3: *Mix design of mortar*

Mix	Cement g	Sand g	Water g	SD g	FA g
PD0	4000	1375	3140	0	0
FASD5	3800	1375	3140	100	100
FASD10	3600	1375	3140	200	200
FASD15	3400	1375	3140	300	300

2.2 Material characterisation

The chemical constituents of the raw materials were analysed using the method of X-ray fluorescence (XRF). Table 1 presents the weight percentages (wt%) of the steel dust, fly ash, and Ordinary Portland Cement (OPC) that were used in the experimental mixes. Additionally, Table 2 presents the specific gravity of the dry samples.

2.3 Mix design

The mortar mixing process was conducted in compliance with the ASTM C305-06 standard, which offers standardized procedures for preparing laboratory specimens of hydraulic cement mortars. The amount of all ingredients was measured precisely based on the specified cement-to-sand ratio of 1:2.75. The number of mortar specimens was 24 specimens that were cured under water at 20°C and 25°C room temperature to ensure proper hydration and strength gain. The amount of cement was variable, sand (1375 g), and water (3140 g) in one batch as shown in Table 3. Furthermore, the partial replacement of cement was conducted using a blend of fly ash and steel dust, each of which contributed equally to the overall replacement percentage (0%,5%, 10%, and 15%). The specimens were named based on their binder compositions. The control specimen without any fly ash or steel dust replacement is labelled as PD0 while those with the combined replacement of both fly ash and steel dust are referred to as FASD specimens. The procedures related to the weighing of materials, casting of specimens, and water curing are shown in Figure 2.

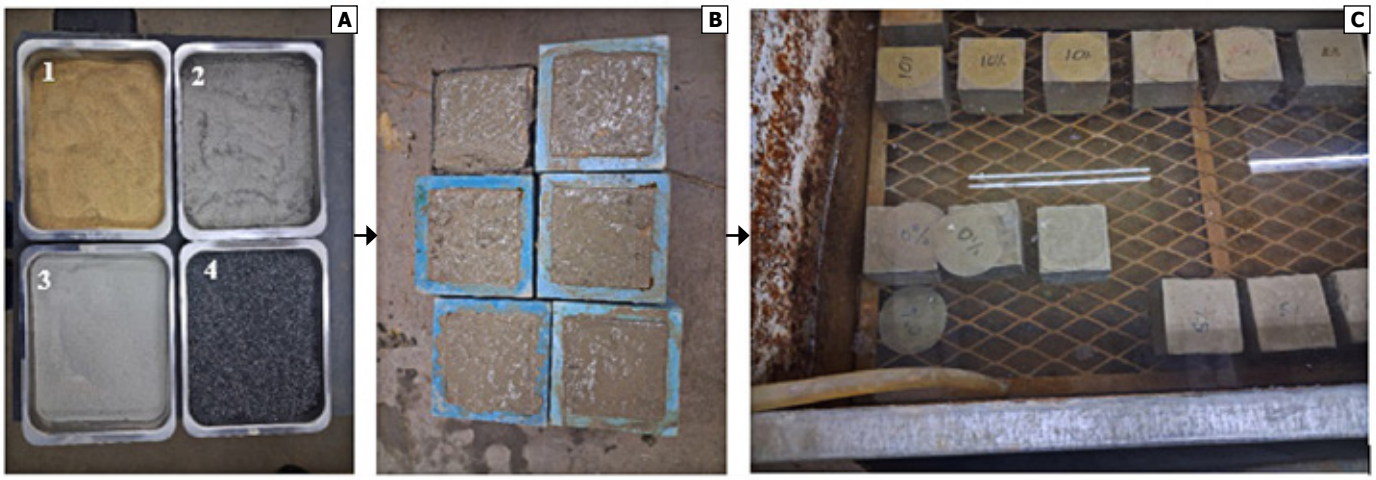


FIGURE 2: *(A) Raw materials - (A1) sand, (A2) legacy ash, (A3) cement, (A4) steel dust; (B) prepared molds; (C) specimens under water curing*

2.4 Testing

The casted samples were evaluated mechanically to determine their density, compressive and flexural strength. The mechanical tests were conducted at curing age 7 days and 28 days, respectively.

2.4.1 Compressive strength

Compressive strength test was conducted using a compression testing machine (CTM), whose loading rate is regulated at 0.9 kN/s (or 1.25 mm/min loading rate depending on the machine settings) according to ASTM C109. Standard cubes were placed in the centre of the platens of the testing machine to ensure an even load application on the sample as depicted in Figure 3. Continuous loading up to failure was conducted on the sample. The maximum load was noted where the failure occurred. The compressive strength of each test cube was determined using the formula (2.1):

$$f_c = \frac{P}{A} \quad (2.1)$$

Where:

f_c = compressive strength (MPa)

P = maximum load at failure (N)

A = loaded area of specimen (mm²)



FIGURE 3: *Compressive strength testing*

2.4.2 Flexural strength

The modulus of rupture of the mortar was investigated to examine its capacity to withstand bending forces while under load. The experiments were carried out in accordance with the ASTM C348 Standard Test Method for Flexural Strength of mortars. The flexural strength was assessed through the flexural bending tests using a displacement-controlled load application method. Rectangular cubes of dimension 200 × 100 × 60 mm were used in the flexural test procedure. In flexural testing, each sample was supported by two steel rods with a clear span of 170 mm, and load was applied at mid-span of the sample in a three-point bending test arrangement.

Figure 4 shows the testing setup. The load was applied at a displacement rate of 2 mm/min until failure occurred. The maximum load at breakage was noted and then used to determine the flexural strength of the mortar. For a three-point bending test, flexural strength is calculated as presented in Equation 2.2:

$$R = \frac{3PL}{2bd^2} \quad (2.2)$$

Where:

- R = flexural strength / modulus of rupture (MPa)
- P = maximum load at failure (N)
- L = span length (mm)
- b = width of specimen (mm)
- d = depth (thickness) of specimen (mm)



FIGURE 4: *Flexural testing machine*

3. RESULTS AND DISCUSSIONS

3.1 Density

The inclusion of FASD resulted in the clear densification of the material with its density ranging between 2240 and 2300 kg/m³ to 2550 and 2600 kg/m³ for 15% FASD presented in Figure 5.

The progressive densification demonstrates the efficiency of FASD on densifying the material, which is due to the dominance of steel dust with high density. The densification is achieved due to the high Fe_2O_3 (70.52 wt%) content in steel dust and high specific gravity (3.50 compared to 2.60 for natural sand). The densification of the material will result in denser packing of particles and thus less pores in the matrix structure.

These outcomes are inconsistent with the results by Phan et al. (2025), who identified decreased unit weights with increased amount of fly ash due to low specific gravity of this component. In this study, the inclusion of steel dust counteracted the effect, making it possible for an overall increase in density despite fly ash inclusion. Therefore, it is possible to conclude that steel dust plays a special role in terms of being not only filler but also densifier.

Furthermore, the higher densities obtained at 28 days in comparison with 7 days prove the continuous hydration and pozzolanic reactions causing pore refinement and matrix densification. This mechanism of densification was noted by Lliso-Ferrando et al. (2025) in the context of recycled brick powder addition that caused porosity reduction and improved durability performance.

The outcome shows that FASD leads to both waste valorisation and microstructure improvement. As a result, the matrix becomes denser and more homogeneous, which means that it will have lower permeability, improved durability and enhanced mechanical performance.

3.2 Compressive strength

The use of FASD led to a marked improvement in compressive strength, which correlated well with the densification of the matrix. As replacement increased from 0% to 10%, the strength increased steadily until 10% was attained, where the compressive strength after 28 days exceeded that of both the control and other modified mixes as indicated in Figure 6. The reason for this improvement is due to better particle packing, low voids, and effective load transfer, facilitated by high Fe_2O_3 content (70.52 wt%) and specific gravity of the steel dust.

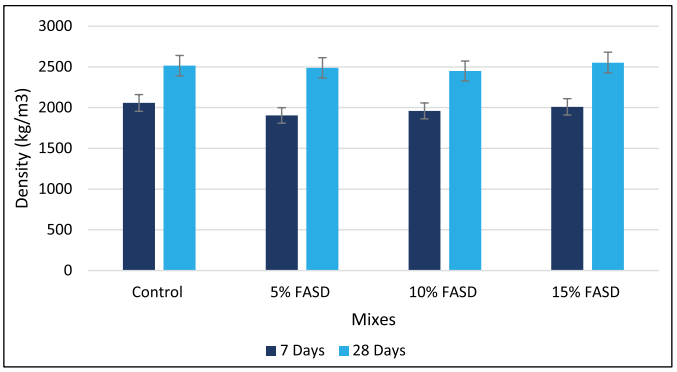


FIGURE 5: *Density of mortar mixes*

As the amount of FASD reached 15%, there was a slight reduction in the compressive strength despite the ongoing process of densification. The reduction indicates that an increase in the amount of LASD leads to a disruption of the binder continuity and introduces microstructural heterogeneities that affect stress transfer effectively.

This pattern conforms with the observations of Phan et al. (2025), who found optimum strength levels in cases of moderate fly ash dosing, while increased replacement ratio negatively affected performance owing to dilution effects despite the continuing pozzolanic reaction. Unlike in fly ash blends, which develop their strength from the development of secondary C-S-H compounds, FASD increases the strength by physical densification and mechanical bonding.

Lliso-Ferrando et al. (2025) similarly confirmed that the use of waste-based binders like recycled brick powder could be maintained and improved with optimized usage mainly through pore refinement and better matrix structure. The 10% FASD is the best combination of mortar mix resulting in maximum compressive strength.

3.3 Flexural strength

It was observed that there was a systematic improvement in flexural strength with an increase in replacement percentage and curing period in the case of modified mortars with FASD. The baseline results for the control mixture showed readings of about 5.5 MPa after 7 days and 6.5 MPa after 28 days. On the other hand, the use of FASD brought about an improvement such that the results were 6.5/7.5 MPa (5%), 7.5/9.0 MPa (10%), and 8.5/10.5 MPa (15%) after 7 and 28 days, respectively as depicted in Figure 7.

The angular shape and surface roughness of the steel dust particles increase the integrity of ITZ, embedding into the cement matrix and inhibiting the development of cracks. The described phenomenon is comparable to the one discovered by Naenudon et al. (2022) with the use of waste fibre cement particles in geopolymer mortars where they served as micro-reinforcements and increased flexural strength with moderate substitution ratios. Consequently, in the case of FASD, the particles do not only densify the matrix but increase its mechanical stability under bending.

A second rationale behind the phenomenon is associated with the filler and nucleation effect. The fine steel dust particles fill the voids in the matrix and serve as the nucleation sites for the formation of C-S-H hydrates, thus increasing the density of the matrix structure. Similarly, Phan et al. (2025) have found out that nano-silica accelerates the hydration process and fills the spaces between binder particles, resulting in higher flexural strength. Even though steel dust cannot be regarded as the pozzolanic material like fly ash, it can contribute to the cement hydration.

Furthermore, the study findings reveal the significance of stress redistribution. Flexural strength is reliant on how much the matrix can withstand tensile stresses, while the presence of FASD increases its resistance by distributing the stresses and delaying cracks from developing. The rationale behind this follows what Lliso-Ferrando et al. (2025) have found in that recycled brick powder decreased the porosity level and increased resistivity, which indirectly improves tensile resistance.

4. CONCLUSIONS

The inclusion of steel dust (FASD) as part of the cement substitution material greatly improved the physico-mechanical properties of the mortar. As the amount of FASD was increased, there was progressive improvement in density, which can be explained by the better densification of the matrix due to the higher specific gravity and filler characteristics of the steel dust. The compressive strength was optimized at 10% substitution as it provided an efficient particle arrangement, good load transfer, and continuous binder phase. Flexural strength, on the other hand, continued to increase with the increase in the FASD content, showing peak strength at 15% substitution due to better crack bridging ability and efficient stress transfer. These findings show the potential of using a combination of fly ash and steel dust it as a sustainable cement replacement in high performance mortars.

5. RECOMMENDATIONS

Future research must concentrate on understanding the microstructural principles underlying the improved properties of the FASD-based mortars. The application of advanced methods of characterization, such as SEM (Scanning Electron Microscopy), XRD (X-ray Diffraction), and MIP (Mercury Intrusion Porosimetry), is vital for identifying the ITZ (Interfacial Transition Zone) development, hydration products formation, and pore structure refinement that all contribute to the properties development. Research

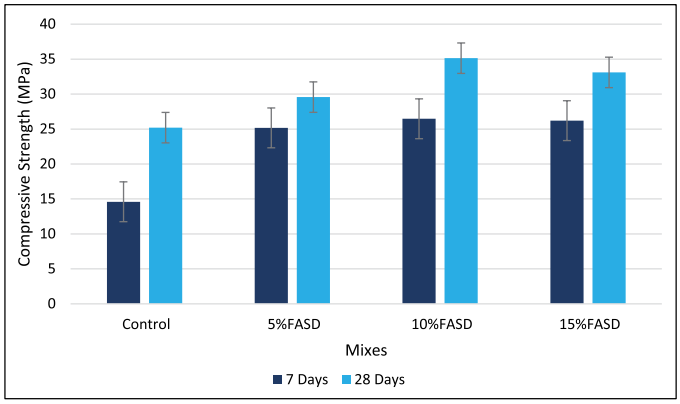


FIGURE 6: *Compressive strength of mortar mixes*

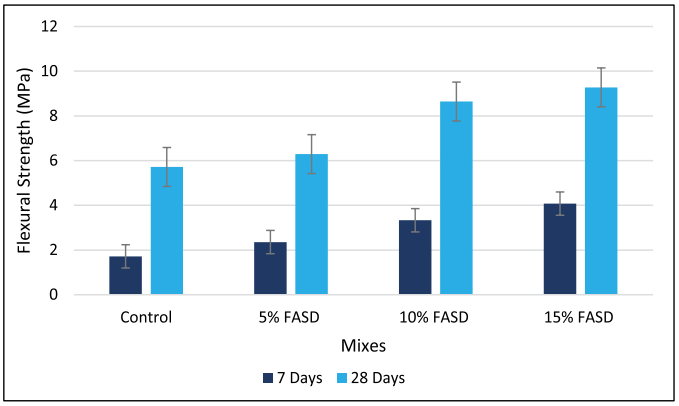


FIGURE 7: *Flexural strength of mortar mixes*

must also move beyond laboratory tests toward full-scale validation of the results in real-life conditions. The properties of FASD-based building materials for both structural and non-structural purposes, for instance, in pavement construction, prefabricated construction, or masonry units, must be thoroughly investigated. The focus should be on their flexural behaviour, crack resistance, and long-term durability under combined mechanical and environmental loading.

Finally, an exhaustive life cycle assessment (LCA) is needed to evaluate the sustainability implications of FASD use. This would include the evaluation of CO_2 reduction, cost-efficiency, and waste revalorization possibilities.

6. REFERENCES

Akinsulire, A. A., Idemudia, C., Okwandu, A. C., and Iwuanyanwu, O. (2024). Sustainable development in affordable housing: policy innovations and challenges. *Magna Sci. Adv. Res. Rev.*, 11, 090–104. doi: 10.30574/msarr.2024.11.2.0112

Arulmoly, B., Konthesingha, C. and Nanayakkara, A. (2021). Effects of blending manufactured sand and offshore sand on rheological, mechanical and durability characterization of lime-cement masonry mortar. *European Journal of Environmental and Civil Engineering*, 26(15), pp.7400–7426. doi:https://doi.org/10.1080/19648189.2021.1995506.

ASTM C109 (2020). *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens).* ASTM International, West Conshohocken, PA.

ASTM C348 (2020). *Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars.* ASTM International, West Conshohocken, PA.

Bărbulescu, A. and Hosen, K. (2025). Cement industry pollution and its impact on the environment and population health: A review. *Toxics*, 13(7), p.587. doi:https://doi.org/10.3390/toxics13070587.

Dobiszewska, M., Bagcal, O., Beycioğlu, A., Goulias, D., Köksal, F., Płomiński, B., Ürünveren, H. (2023). Utilization of rock dust as cement replacement in cement composites: an alternative approach to sustainable mortar and concrete productions. *Journal of Building Engineering*, 69, 106180. https://doi.org/10.1016/j.jobe.2023.106180

Fayomi, G. U., Onyari, E. K., and Mini, S. E. (2024). Evaluating social housing potential for low-income urban dwellers in Johannesburg. *Case Studies in Chemical and Environmental Engineering*, 9:100737. doi:10.1016/j.cscee.2024.100737

Gehlot, M. R. and Shrivastava, S. (2024). Sustainability assessment of granite cutting waste incorporated cement sand rendering mortar: Technical, environmental, cost, and social parameters. *Journal of Cleaner Production*, 480, 144108. doi:https://doi.org/10.1016/j.jclepro.2024.144108.

Gupta, R., Gregg, M., Lalande, C., and Herda, G. (2015). *Green building interventions for social housing*. Nairobi: UN-Habitat.

Hamada, H. M., Abed, F., Humada, A. M., Al, M. S., Majdi, A., Yousif, S. T. and Thomas, B. S. (2023). Effect of silica fume on the properties of sustainable cement concrete. *Journal of Materials Research and Technology*, 24, pp.8887–8908. doi:https://doi.org/10.1016/j.jmrt.2023.05.147.

Housing Development Agency (HDA) and National Association of Social Housing Organisations (NASHO) (2013). *Reviving our inner cities: social housing and urban regeneration in South Africa*. Johannesburg: Housing Development Agency.

Jabbar, A. (2023). Using cementitious materials to enhance concrete properties and improve the environment: A review. *Wasit Journal of Engineering Sciences*, 11(3), pp.140–154. doi:https://doi.org/10.31185/ejuow.vol11.iss3.482.

Lliso-Ferrando, J. R., Arenos-Barrachina, A., Monzon-Bello, P. and Valcuende, M. (2025). Durability of mortars with partial cement replacement by recycled brick powder. *Applied Sciences*, 15, 4133. https://doi.org/10.3390/app15084133

Ludick, A., Dyason, D., and Fourie, A. (2021). A new affordable housing development and the adjacent housing-market response. *South African Journal of Economic and Management Sciences*, 24:a3637. doi:10.4102/sajems.v24i1.3637

Madisha, M. G., and Khumalo, P. (2021). Social housing policy implementation challenges in South African local municipalities. In: *6th Annual International Conference on Public Administration and Development Alternatives*. Pretoria, South Africa: University of South Africa.

Mironyuk, I., Tatarchuk, T., Paliychuk, N., Heviuk, I., Horpynko, A., Yarema, O. and Mykytyn, I. (2021). Effect of surface-modified fly ash on compressive strength of cement mortar. *Materials Today: Proceedings*, 35, pp.534–537. doi:https://doi.org/10.1016/j.matpr.2019.10.016.

Mohammed, B. K. and Al-Numan, B. S. (2024). Effectiveness of limestone powder as a partial replacement of cement on the punching shear behavior of normal- and high-strength concrete flat slabs. *Sustainability*, 16(5), 2151. doi:https://doi.org/10.3390/su16052151.

Naenudon, S., Vilaivong, A., Zaetang, Y., Tangchirapat, W., Wongsa, A., Sata, V. and Chindaprasirt, P. (2022). High flexural strength lightweight fly ash geopolymer mortar containing waste fibre cement. *Case Studies in Construction Materials*, 16, e01121. doi:https://doi.org/10.1016/j.cscm.2022.e01121.

Ngema, N. N., Bokhari, A. and Mbanga, S. L. (2025). Assessing the impact of social housing on urban regeneration in South African cities. *Frontiers in Sustainable Cities*, 7:1468964. doi:10.3389/frsc.2025.1468964

Phan, V. T.-A., Tran, H.-B. and Vo, V.-T. (2025). Potential usage of fly ash and nano silica in cement mortar for a sustainable construction. *Transportation Research Procedia*, 85, pp.135–142. doi:https://doi.org/10.1016/j.trpro.2025.03.143.

Rajput, S. P. S. (2018). An experimental study on crushed stone dust as fine aggregate in cement concrete. *Materials Today: Proceedings*, 5, 17540–17547. https://doi.org/10.1016/j.matpr.2018.06.070

Zintle Mahlati (2023). Government increases the money it spends on RDP, social housing. *News24*. Available at: https://www.news24.com/politics/government-increases-the-money-it-spends-on-rdp-social-housing-20230331