

The Workability, Buildability and Compressive Strength of Printing Concrete Using Rice Husk Ash and Rubber Crumb

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Abstract

3D printing is computer-controlled to create three-dimensional shapes based on a digital model in the successive layering of materials. It is important that the fresh concrete used in 3D printing has good workability, buildability, and compressive strength to prevent the printable concrete layer from collapsing or deforming beyond acceptable limits. This objectives research was focusing on the interplay between workability, buildability, and compressive strength. incorporating with rice husk ash (RHA) and rubber crumb as sustainable replacements for cement and sand in printing concrete. Six concrete mixtures were investigated three control mixes with varying water-cement ratio (w/c) and superplasticizer content, and three replacement mixes incorporating 20% RHA and 10% rubber crumb alongside adjustments to maintain workability. From the study, it is found that slump tests revealed a strong negative correlation between w/c ratio and superplasticizer content with slump, confirming their influence on workability. Adding RHA and rubber decreased slump slightly for all replacement mixtures compared to their controls. The buildability of the concrete was measured by the yield stress measurements at 0, 10, 20, and 30 minutes after mixing, it showed expected increases over time due to hydration and setting. Control mixtures with lower w/c ratio and higher superplasticizer exhibited lower yield stress and improved flowability, suggesting better buildability. All replacement mixtures had higher yield stress than their controls at all time points. Compressive strength testing after 28 days of curing revealed that two replacement mixes achieved the acceptable Grade 35 standard. The mixture with the intermediate w/c ratio and higher superplasticizer content among the replacements displayed the highest compressive strength, highlighting the importance of optimizing mix design to compensate for the slight strength reduction due to RHA and rubber.

1. Introduction

Over the recent years, 3D printing technology has found extensive applications in architectural design, industrial manufacturing, aerospace, biological engineering, cultural relics protection, and various other industries. Its widespread adoption is attributed to its benefits of cost-effectiveness, high efficiency, robust design capabilities, and dependable quality (Keleş et al., 2017). Notably, the combination of 3D printing technology with concrete technology has emerged as a particularly innovative approach, offering novel possibilities for the advancement

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and utilization of concrete materials. 3D printing concrete, also known as concrete additive manufacturing or 3D concrete printing, is a construction technology that allows for the fabrication of complex concrete structures using a computer-controlled printing process. The technology of three-dimensional printing concrete (3DPC) represents an innovative construction method, predominantly employing layered extrusion for depositing material. In this process, concrete is extruded through a nozzle and systematically deposited layer by layer, following a digitally designed printing route, all without the need for any formwork (Han et al., 2021). Since the invention of the first 3D printer in 1983, the development of this technology has been improving fast paced (Nadarajah, 2018). Demonstrated evidence indicates that 3D printing technology offers advantages such as high efficiency and flexibility, along with environmental benefits, whether applied to the construction of complex-shaped structures or the printing of ordinary right-angle walls (Xiao, 2021).

Earlier research has indicated that utilizing 3D printing (3DP) technology in construction can result in a reduction of 30–60% in construction wastes, a decrease of 50–80% in labor costs, and a shortened production time by 50–70% (Winsun, 2016). On the other hand, the usage of this technology is much more recent in buildings. According to Berman, 3-D printing employs an additive manufacturing process whereby products are built on a layer-by-layer basis, through a series of cross-sectional slices (Berman, 2012). In Figure 1.1, a comparison is presented between traditional construction methods and 3D printing (3DP) construction. The illustration reveals that conventional construction relies heavily on human resources across different phases, making it a time-consuming and costly process. Moreover, conventional construction results in a substantial generation of construction waste. In contrast, 3D printing operates mostly in an automated fashion, constructing buildings directly from a computer-aided design (3D-CAD) with minimal human intervention. Notably, 3D printing eliminates the need for tooling, dies/formwork, and fixtures (Tay et al., 2017). Thus, this method reduces many manual processes, labor requirements, and material waste.

Conventional concrete types pose challenges for 3D printing due to issues such as aggregate jamming in the nozzle, compacting obstacles, and space limitations arising from the installation of rebar and formwork (Tay et al., 2017). Presently, ongoing research endeavors are directed towards finding or adapting concrete materials suitable for 3D printing, ensuring they possess the necessary mechanical properties and capabilities for continuous extrusion and layering (Allouzi et al., 2022).

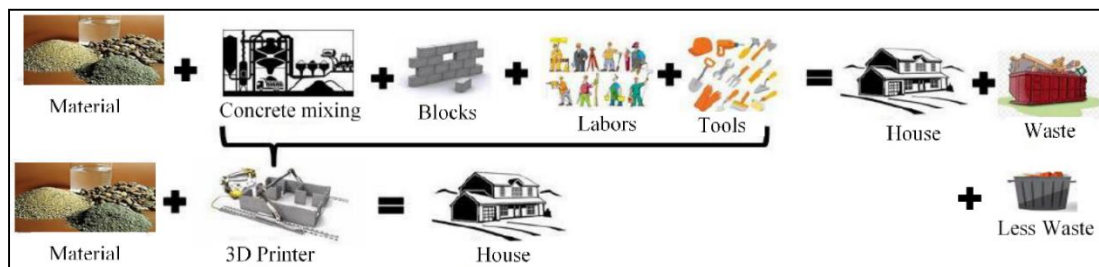


Fig. 1 Conventional construction vs 3D printing construction process (Nadrajah, 2018)

2. Material and Methodology

2.1 Material

- Cement

In the construction field, the application of cement differs depending on the characteristics, composition, and intended use of the material. This study focuses on the utilization of Ordinary Portland cement (OPC), which is commonly employed in the construction industry for creating concrete and concrete. OPC serves the purpose of binding together all the components utilized in concrete or concrete mixtures. It is crucial to handle the cement with caution to prevent any compromise in its performance and efficacy.

- Coarse aggregate

3DPC with coarse aggregates with a maximum particle size of 20 mm. The results showed that the paste-aggregate ratio has a significant effect on the printability of 3DPC (Chen, 2020).

- Sand

Fine aggregates were employed in the production of 3D printing concrete. These small-sized aggregates play a crucial role in filling the empty spaces within the concrete mixture. To assess their size distribution, the sand was subjected to a sieving process in accordance with the standards outlined in BS EN 993:2012 (BSI, 2005). The sand was required to pass through a 2 mm sieve.

- Water

Water is an essential component of the concrete mix design and has a significant impact on how well the mix design performs. The precise amount of water that was utilised in the concrete mixture was determined. This is so because the water to cement ratio was what determined how well the mix design performed. Since it met the requirements of BS EN 1008-2002, the water used in the mix proportions in this study was taken from the laboratory's fresh tap water.

- Rice husk ash

From the closest facility, rice husk ash was obtained. To substitute cement in a concrete mixture, the particle size of RHA is crucial. It thus went through a sieve with an aperture of 300 μm (Molaei Raisi et al., 2018). The finer RHA are more responsive than coarser ones (Adesina & Olutoge, 2019)

- Rubber

The size of the crumb rubber must be smaller than 3 mm since it will be used to replace the fine aggregate. The used crumb rubber is untreated and already in fine sizes. Therefore, the fine aggregate replacement in the concrete mixture was made up of crumb rubber particles measuring 1 to 3 mm. To replace the precise quantity of fine particles in the concrete mixes, the volume of crumb rubber must be calculated. The rubber crumbs were treated using 10% of NaOH concentrations (by volume). The rubber crumbs were initially stirred uniformly in a NaOH solution to ensure consistent treatment and subsequently soaked for a duration of 40 minutes. Following this, the crumbs underwent a thorough rinse with water. Subsequently, the crumbs were left to dry at room temperature for 24 hours.

- Superplasticizer

Superplasticizers are innovative water-reducing agents that, when incorporated into concrete, enhance its workability substantially without compromising its strength. In this study, concrete was prepared by adding the superplasticizer at a dosage of 0.5% to 1% relative to the total weight of the cement.

2.2 Mix design and testing

The concrete mix design has a significant impact on both the 3D printing of cementitious concrete and the structural use of the printed concrete segments. The test, which used rice husk ash and rubber as the binder was done to figure out the workability, buildability, and compressive strength of concrete. Total of eighteen cubes are tested at 0.33, 0.34 and 0.35 water-cement ratios with 0.5 to 1 percent of superplasticizer and total of six sample mixtures.

Table 1 3D printed concrete mix proportion.

Sample	Cement replaces by RHA (%)	Sand replaces by rubber crumb (%)	w/c ratio	Binder (kg)			Aggregate (kg)			Water (kg)	Sp (%)
				Cement	RHA	Sand	RC	Coarse aggregate			
Set I	0	0	0.33	10.96	0	11.72	0	16.87	3.62	1	
			0.34	10.96	0	11.72	0	16.87	3.73	0.5	
			0.35	10.96	0	11.72	0	16.87	3.84	0.5	
Set II	20	10	0.33	10.6	0.36	11.37	0.35	16.87	3.62	1	
			0.34	10.6	0.36	11.37	0.35	16.87	3.73	0.5	
			0.35	10.6	0.36	11.37	0.35	16.87	3.84	0.5	

Batching the concrete mixture began with preparing the necessary materials. Following the guidelines in BS 1881: Part 125: 1983, which specifies the procedures for mixing and sampling fresh concrete, the materials were batched and mixed, as shown in Fig 2(a). The workability of the mix was then assessed using a slump test conducted in accordance with the requirements of BS EN 12350-2:2009 as shown in Fig 2(b). To ensure the fresh concrete in the range of slump, superplasticisers, workability control substance was used to control workability.



Fig. 2 (a) Batching concrete; (b) Slump test

Concrete cubes sized 100 mm x 100 mm x 100 mm were manufactured to assess their compressive strength following the confirmation of the concrete mix meeting essential workability criteria through a slump test. Additionally, the buildability was evaluated using a shear vane test. The shear vane test involved assessing the concrete mix for 0, 10, 20, and 30 minutes to ensure it met the necessary workability standards. The purpose of the shear vane test is to determine the buildability of the concrete, and this evaluation was carried out utilizing a shear vane apparatus, as illustrated in Fig. 3(a). Subsequently, concrete samples from each mix design underwent a 28-day curing process, and Fig. 3(b) depicts the execution of the compressive strength test.

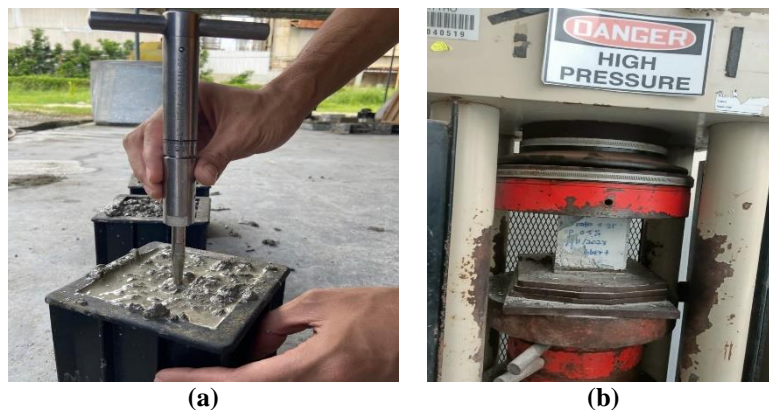


Fig. 3 (a) Shear vane test; (b) Compressive strength test

3. Result and Discussions

3.1 Workability

The slump height is a measure of the workability of the concrete. A higher slump height indicates that the concrete is more workable and will flow more easily. From Fig 4, for the control mixtures, lower w/c ratio content led to lower slump (less fluid). The lowest w/c ratio, which is 0.33, has the lowest slump and is the least fluid. While the highest w/c ratio, which is 0.35, has the highest slump and is the most fluid. For the replacement mixtures, adding RHA and rubber crumb reduces the slump. All replacement mixtures have lower slump values than their corresponding control mixtures. This shows that replacing cement with RHA and sand with rubber crumb slightly reduces the workability of the concrete. However, incorporating RHA and rubber crumb is still acceptable since the design slump by using DOE method is range between 30mm to 60mm and can be achieved while maintaining acceptable workability by adjusting the mix design, particularly the w/c ratio and superplasticizer content.

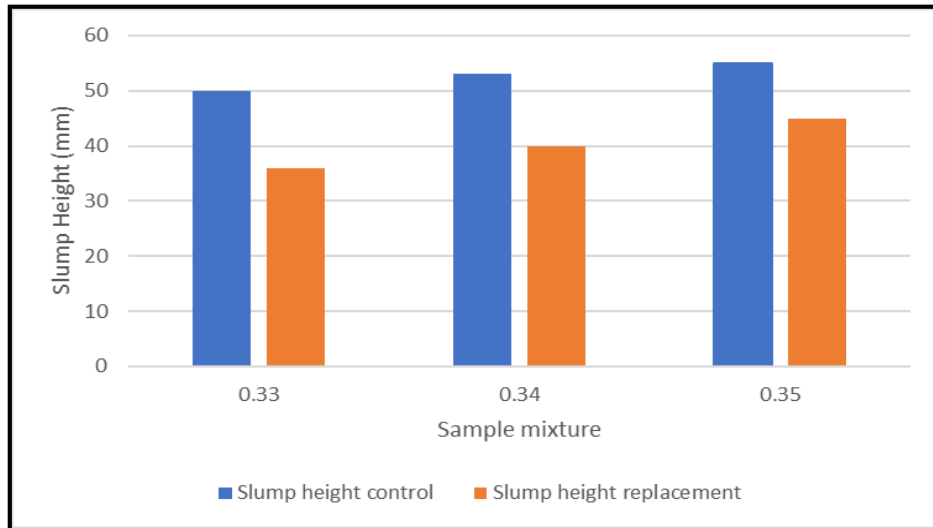


Fig. 4 Slump height bar chart for six different concrete mixtures at different w/c ratio

3.2 Buildability

From Fig 5, it can be observed that yield stress increases for all control mixtures (S1, S2, S3) over time due to hydration and setting. This is expected behavior as the concrete thickens and becomes less flowable. S1 with the lowest w/c ratio and highest superplasticizer has the lowest yield stress at all time points. This suggests it's the least flowable but most workable due to the superplasticizer's effect. S3 with the highest w/c ratio, lower superplasticizer has the highest yield stress at all time points. This indicates it's the most flowable but least workable due to the higher water content and lower superplasticizer dosage. All replacement mixtures (S4, S5, S6) have higher yield stress values than their corresponding control mixtures at all time points. By adding RHA and rubber, the concrete is more viscous. S1 with higher superplasticizer dosage have lower yield stress and potentially better buildability than S2 and S3 same goes to its corresponding replacement mixtures, S4 with higher superplasticizer dosage potentially to have better buildability compared to S5 and S6. Using an appropriate superplasticizer dosage can help compensate for the viscosity increase caused by RHA and rubber, improving the buildability of replacement mixtures. While RHA and rubber crumb increase viscosity, optimizing w/c ratio and superplasticizer content can manage it for good buildability.

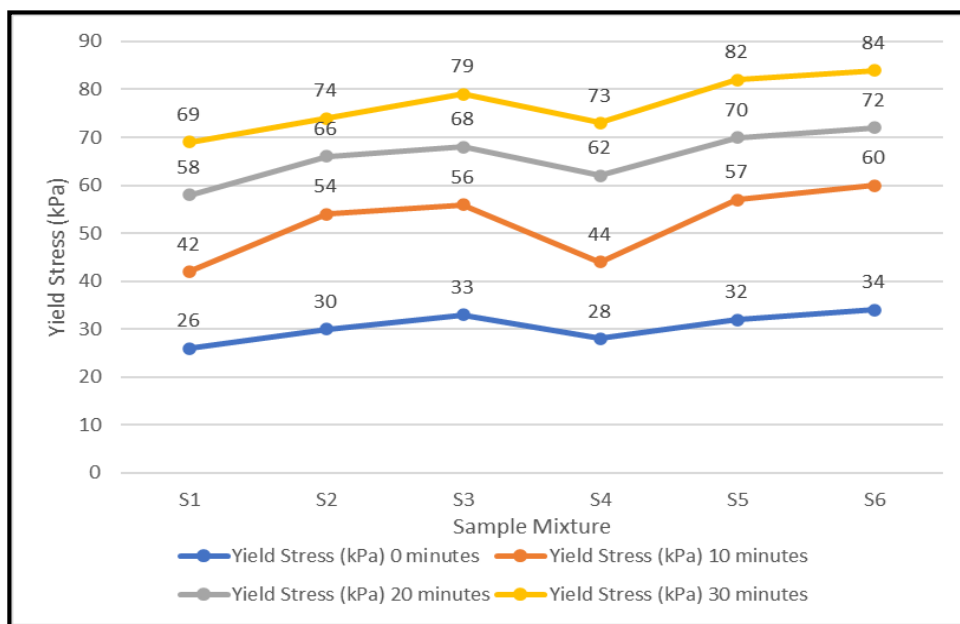


Fig. 5 Yield stress graph for six different concrete mixtures on 0, 10, 20 and 30 minutes

3.3 Compressive Strength

Fig. 6 shows the comparison of the compressive strength between the control mixtures and replacement mixtures. For control mixtures, all achieved DOE target strength which is 48 MPa after 28 days. For the replacement mixtures (S4, S5, S6), none of them reached the DOE target strength. However, S4 (0.33 w/c ratio, 1% superplasticizer) and S5 (0.34 w/c ratio, 0.5% superplasticizer) achieved strengths acceptable for Grade 35 concrete. S6 (0.35 w/c ratio, 0.5% superplasticizer) had the lowest compressive strength among the replacements. From the observation, a higher w/c ratio generally leads to lower compressive strength. S4 with the intermediate w/c ratio and lower superplasticizer content achieved the highest strength among replacements. While RHA and rubber replacements slightly decrease strength, using the right mix design (e.g., 0.34 w/c ratio, 0.5% superplasticizer) can achieve acceptable strength for specific applications like Grade 35 concrete.

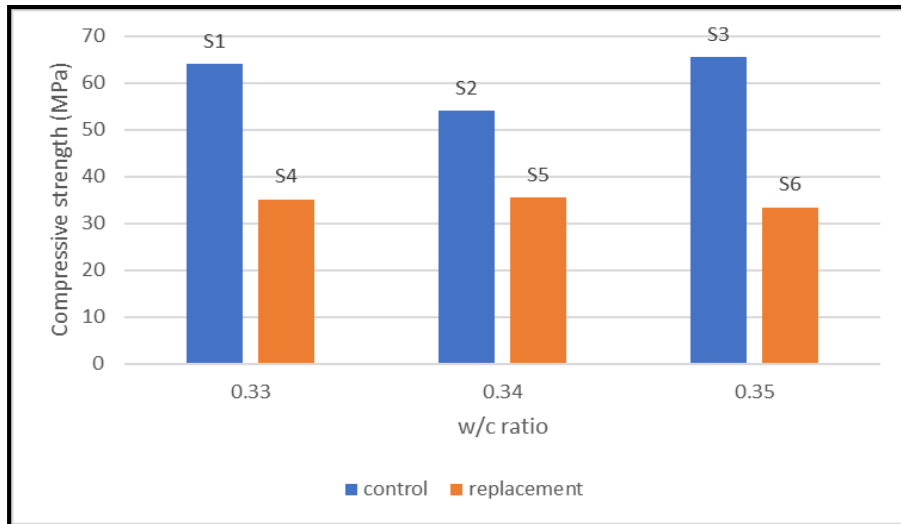


Fig. 6 Compressive strength bar chart for six different concrete mixtures

3.4 Relationship between slump and yield stress

Fig. 7 shows the relationship between the slump and yield stress. The results show as the slump height increases; the yield stress also increases. The R^2 value is 0.0136, indicating a very weak positive relationship between slump height and yield stress. An R^2 value of 1 would indicate a perfect positive relationship, while an R^2 value of 0 would indicate no relationship at all. Therefore, in this case, the relationship between slump height and yield stress is weak.

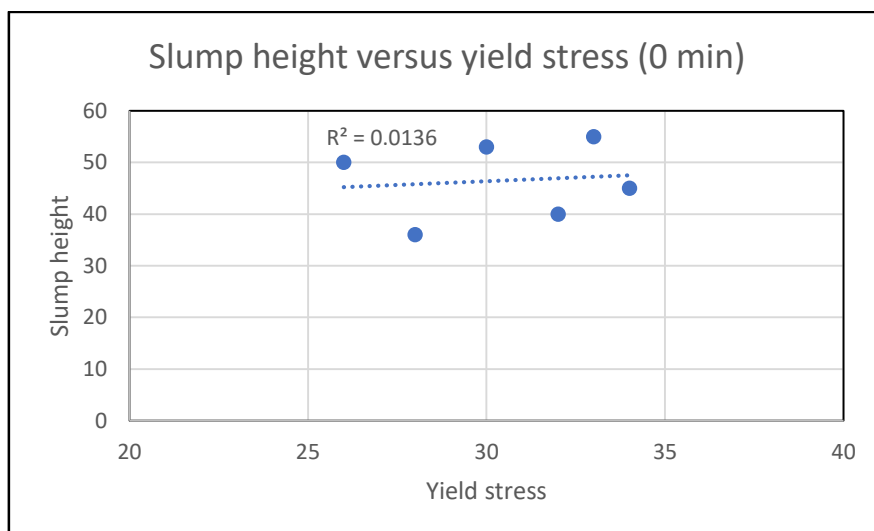


Fig. 7 Relationship between slump and yield stress

3.5 Relationship between slump and compressive strength

Based on the graph shown in Fig 8, we can observe a positive linear relationship between slump height and compressive strength. As the slump height increases, the compressive strength also tends to increase. This indicates that as the slump height increases, the concrete mix tends to develop a higher degree of compressive strength. The R^2 value, or coefficient of determination, is 0.727, indicating that about 72.7% of the observed variation in compressive strength can be explained by the observed variation in slump height. It is important to note that the actual strength of concrete can vary due to various factors, such as the type of aggregate, the water-to-cement ratio, and the curing conditions. Therefore, the observed relationship in this graph should be interpreted within the context of these variables.

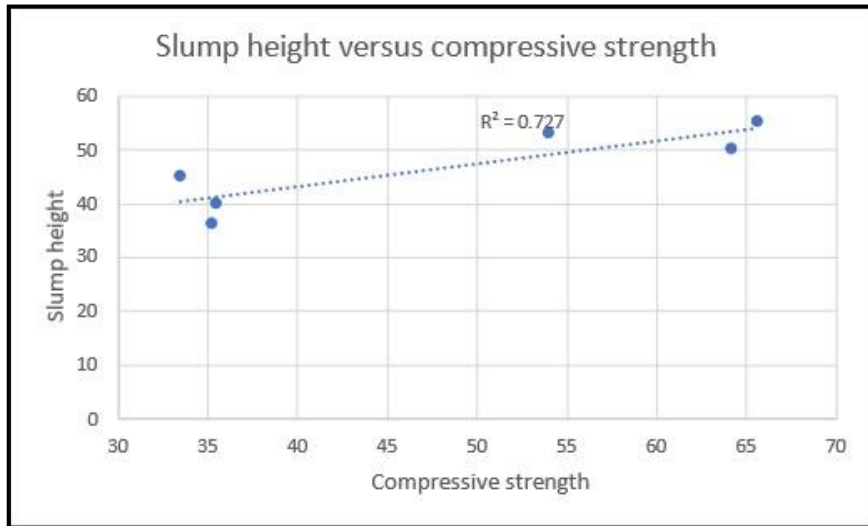


Fig. 8 Relationship between slump and compressive strength

3.6 Relationship between yield stress and compressive strength

Fig. 9 shows the relationship between the yield stress and compressive strength. The results show a linear relationship between yield stress and compressive strength. This means that as compressive strength increases, the yield stress also tends to increase proportionally. The relationship between yield stress and compressive strength, as depicted in the graph, appears to be linear with a low level of correlation ($R^2 = 0.0891$). In terms of practical implications, a lower R^2 value suggests that there is considerable randomness in the data, and it may not be accurate to draw general conclusions about the relationship between yield stress and compressive strength based on this graph alone. This underscores the importance of considering additional factors, such as temperature, loading rate, and the specific materials used in the test, when attempting to understand and predict the behavior of real-world materials.

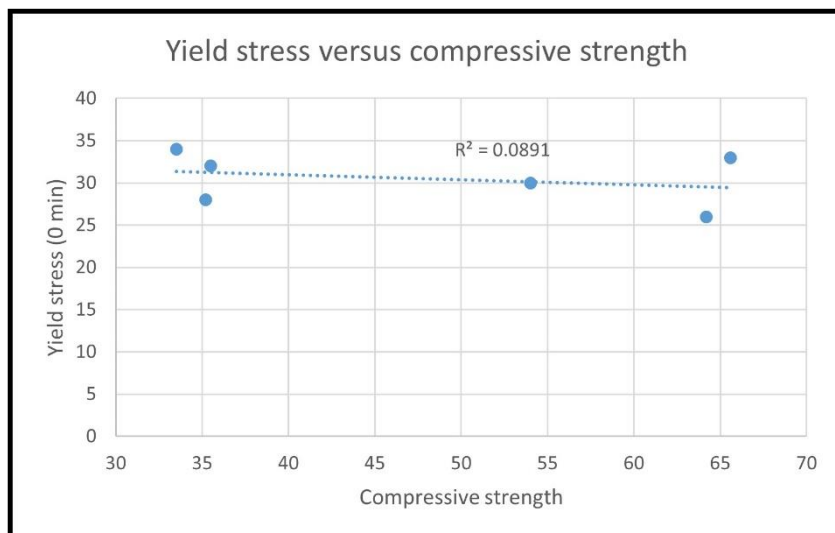


Fig. 9 Relationship between the yield stress and compressive strength

4. Conclusions

The present investigation leads to the following conclusion:

- For the workability of concrete, it is increase as the w/c ratio increased. RHA and rubber crumb slightly reduce workability, their impact but it is manageable. The mixture with higher w/c ratios and superplasticizer content have higher workability. Incorporating RHA and rubber crumb might affect workability but can be managed by adjusting the mix design, particularly the w/c ratio and superplasticizer content.
- For buildability of concrete, RHA and rubber crumb additions generally increase concrete viscosity but the effect may soften over time. Lower w/c ratios and lower superplasticizer content in control mixtures lead to higher viscosity overall. The implication for buildability is lower yield stress indicates better flowability and potentially easier printing. However, excessively low yield stress could lead to slumping or loss of shape during printing. Finding the optimal balance between yield stress and other properties like compressive strength is crucial for successful printing.
- For the compressive strength of the concrete, Higher w/c ratio generally leads to lower compressive strength. Replacing cement with RHA and rubber is viable for certain applications while considering its minor impact on strength and adjusting the mix design for optimal results. Further optimization of the replacement mixture might be possible for achieving the DOE target strength. Additional research would be needed to improve the strength of mixes with higher w/c ratios.

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