Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 46 No. 1 (2025)

Experimental Study on Mechanical Properties of Self-Compacting Concrete with Silica Fume and Stone-Polishing Dust

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Abstract:

With the need for alternative sustainable building materials increasing day by day, utilizing industrial by-products to reduce the environmental impact of conventional concrete production has been of interest. Manufacturing Ordinary Portland cement (OPC) which is an energy-intensive process is one of the foremost contributors to carbon footprints in the construction industry. Many researchers have attempted to solve this problem with different pozzolanic materials and have discovered some of the best materials for replacing OPC which include silica fume (SF) and stone polishing dust (SPD). As a by-product of silicon and the ferrosilicon alloy Silica Fume, a pozzolanic material, and SPD, another by-product of the stone polishing industry, can serve as viable options to improve the mechanical properties and durability characteristics of conventional concrete mixes. Similarly, the use of natural fine aggregate in concrete degrades natural resources and the environment as well. As a partial substitute for fine aggregate, Granite stone dust (GSD), a by-product of granite processing, is a sustainability option. Utilizing GSD in concrete both mitigates waste disposal issues and economizes natural resources. In this study, the effect of SPD, SF, and GSD on the mechanical properties of the self-compacting concrete (SCC) is investigated. SPD and SF were used to replace OPC at levels of 5%, 10%, 20%, and 30% by weight and GSD was incorporated as a 15% replacement for fine aggregate. An experimental program was conducted to measure the compressive strength, split tensile strength, and flexural strength of SCC specimens cured under water at 7, 14, 28, and 90 days. The results show that by including these by-products the mechanical properties of SCC are greatly improved.

Keywords*:* Self-Compacting Concrete, Silica Fume, Stone-Polishing Dust.

1. Introduction

It is a critical challenge for the construction industry to balance between its need of materials and environmental sustainability. Consequently, production of the traditional concrete is heavily dependent on the usage of Ordinary Portland cement (OPC) which contributes to significant carbon footprint [1]. It is extremely energy intensive, and contributes to large CO_2 emissions, making OPC a key contributor to climate change [2]. This has led researchers to look at alternative materials that can minimize reliance on OPC while retaining, at the very least, equivalent or improved mechanical properties of concrete.

Industrial by products can act as cement and aggregate substitutes and are one of such reliable alternatives. Two such by products are stone polishing dust (SPD) and silica fume (SF) that can show significant impact in concrete manufacturing. SPD, created in abundance during stone polishing, is an environmental hazard and a disposal issue of concern. However, its use as a partial substitute of OPC can resolve the waste management problems and improve the sustainability of concrete production. Due to its pozzolanic properties, it has emerged as a potential sustainable OPC replacement [3].

Several studies have been conducted to explore use of SPD as a partial replacement for OPC in concrete mixture [3], [4]. At appropriate replacement levels, SPD can improve the mechanical properties of concrete, mainly in terms of compressive strength [4]. [3] observed an increase in compressive strength of up to 20% when SPD was partly replaced by OPC. Nevertheless, this points out that excessive SPD content may adversely affect the workability of the concrete mix, resulting in poor compaction and lower strength [4].

The liquid produced as a by-product of silicon smelting is referred to as SF, which is a highly reactive pozzolanic material. Because of its very fine particle size and high silica content it offers enhanced strength, durability and impermeability of concrete [5], [6].

There are many research studies on the use of SF as a partial substitute for OPC in concrete mixes [6], [7], [8]. Nevertheless, these studies have repeatedly proven that SF can enhance the mechanical properties of concrete, particularly the compressive strength, flexural strength and split tensile strength [5], [6], [7]. SF replacement level varies according to the specific mix design and the properties being targeted. Past studies has revealed that the range of SF that can be added without affecting the performance is in the range of 5 to 15 percent by weight of OPC [9].

Studies have shown that the addition of SPD and SF can significantly enhance the compressive strength of SCC, particularly at early ages [9]. [10] examined the use of SPD and SF in SCC and found that the addition of these by-products improved self-compaction criteria, flowability and viscosity of the concrete.

However, it is the optimal replacement levels SPD and SF that are important in attaining the desirable strength improvement. A number of studies have indicated that compressive strength can decrease when the maximum packing occurs beyond the optimal range as a result of factors such as poor particle packing, lower hydration, and increased porosity [11], [7].

Natural fine aggregate in concrete production has a major environmental impact associated with the depletion of natural resources and environmental degradation [1]. Granite stone dust (GSD), a by-product of granite processing, can be utilised as partial replacement for fine aggregate as a sustainable alternative [12]. Utilizing GSD addresses two key environmental concerns: it handles waste disposal issues related to granite industry, and lesser usage of the natural resources [13]. The use of GSD as a fine aggregate replacement in SCC has been studied in detail in several studies [1]. It has been demonstrated that the inclusion of GSD as fine aggregate replacement improved the strength and durability of SCC, thus encouraging sustainability. [3] Also found that GSD could perform as a sustainable substitute for fine aggregate, by addressing both issues of waste disposal and conserving natural resources. These results highlight the potential of GSD to aid in a more sustainable concrete production process [14].

SPD and SF can provide pozzolanic properties contributing to increased strength and durability while GSD is a sustainable fine aggregate alternative to natural fine aggregate, reducing environmental impact. The consistent findings across several studies imply that SPD, SF, and GSD in SCC leads to SCC material with comparable or better mechanical properties than the conventional SCC.

Given these findings, this research focuses on the combined use of SPD, SF, and GSD in the production of self-compacting concrete (SCC). The mechanical performance of SCC with various levels of SPD and SF as OPC replacement and GSD as fine aggregate replacement was studied. The research explored the compression strength, split tensile strength, and flexural strength at different ages of curing to better understand the potential benefits and applications of these sustainable materials in present day construction.

2. Materials

Ordinary Portland Cement (OPC) of Grade 53 was utilized for all concrete mixes. The cement adhering to IS: 12269-1987 specifications and a normal consistency of 36% with a specific gravity of 3.17 was used. Table 1 shows the physical property of OPC 53 grade used.

The fine aggregate (FA) used was natural river sand, with a specific gravity of 2.68 and water absorption of 0.78%. It was classified as Zone II according to IS 383:2016. Coarse aggregate (CA) consisted of 10 mm and 20 mm

graded particles, with specific gravities of 2.74 and 2.71 and water absorption of 0.91% and 0.82%, respectively. Table 2 shows the material basic properties of collected aggregates. Figure 1 shows the particle distribution curves of coarse and fine aggregates.

Granite Stone Dust (GSD), a by-product obtained from a granite quarry, served as a partial replacement for FA. The specific gravity of GSD was 2.31, water absorption was 1.21%, and fineness modulus was 2.71. Table 3 shows the physical Properties of Granite Stone Dust

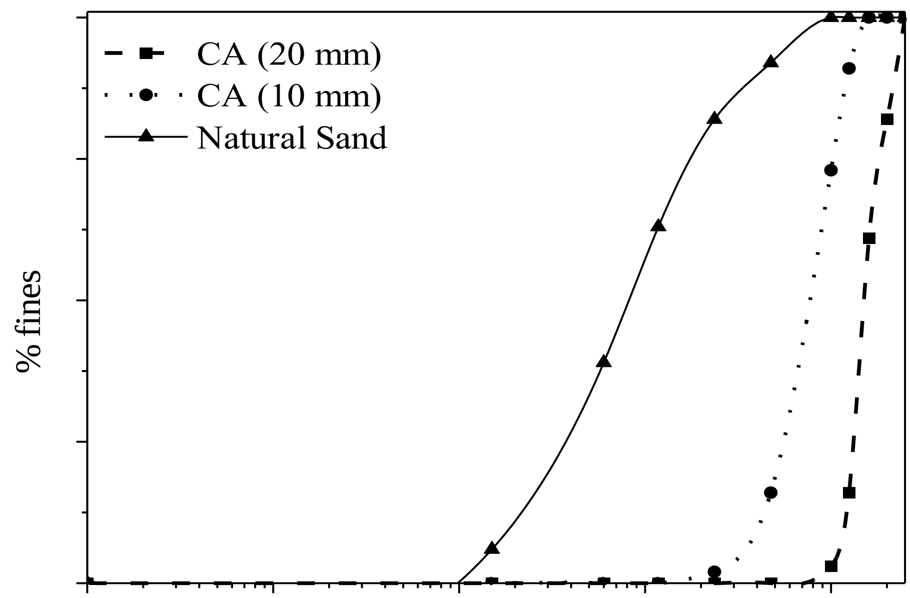
Stone Polishing Dust (SPD) and silica fume (SF) were used as partial replacements for OPC with replacement levels of 5%, 10%, 20%, and 30% by weight of OPC and GSD was maintained at 15% replacement for fine aggregate. Table 4 shows the chemical Composition of Stone Polishing Dust

Naphthalene based superplasticizer (Conplast SP430) was added at 1.2 % of total binder weight to achieve the workability. It of A viscosity modifying agent (VMA) was also included at 0.2% of binding weight to stabilize the mix especially for higher replacement levels.

The pH of the water used for mixing and curing was 7.3 which is potable water and fit for concrete production.

Table 1. Physical property of OPC 53 grade used

Physical Property	**Test value**	**Specifications as per IS 12269-1987**
Normal consistency	36%	---
Initial setting time (min)	37	≥ 30 minutes
Final setting time (min)	271	≤ 600 minutes
Soundness	1.5	≤ 10 mm
Specific gravity	3.17	≥ 3.15



100

75

50

25

0

0.001 0.01 0.1 1 10

Sieve size (mm)

Figure 1. Particle distribution curves of coarse and fine aggregates

able 2. Material basic properties of collected aggregates

Basic Property	**Coarse aggregates**		**Fine aggregates**
	10 mm	**20 mm**	
Specific Gravity	2.74	2.71	2.68
Water absorption	0.91	0.82	0.78
Gradation of FA	-	-	*Zone-II*

Table 3. Physical Properties of Granite Stone Dust

Physical Property	**Granite Stone Dust**
Specific Gravity	2.31
Water absorption	1.21
Fineness modulus	2.71
% fines < 40 microns	9.2

Table 4. Chemical Composition of Stone Polishing Dust

Components	**Content (%)**
Silicon-di-oxide (SiO_2)	23.1%
Aluminium tri oxide (Al_2O_3)	4.2%
Ferric oxide (Fe_2O_3)	2.1%
Calcium oxide (CaO)	38.9%
Magnesium oxide (MgO)	2.4%
Titanium oxide (TiO_2)	1.2%
Potassium oxide (K_2O)	2.3%

3. Results & Discussion

3.1 Compressive strength

The compressive strength of the control mix (0% SF+SPD) after 7 days was 19.48 MPa, which increased partially to 25.37 MPa at 14 days, 42.85 MPa at 28 days, and 48.31 MPa at 90 days. Compressive strength test result is shown in Table 5 and Figure 2. With the hydration of OPC and the gradual densification of the concrete matrix, these results show an increase in strength as time increases. For the mix with 5% replacement of SPD and SF 7-day compressive strength is 20.69 MPa, which further increased to 25.99 MPa at 14 days, 43.28 MPa at 28 days, and 48.53 MPa at 90 days. A similar trend is observed at 10% replacement, with the 90-day compressive strength reaching 49.28 MPa, signifying a modest improvement due to the combined pozzolanic and filler effects.

The highest compressive strength is achieved by the mix with a 20% replacement level, where the 90-day strength reached 49.79 MPa, reflecting the optimum performance of SPD, SF, and OPC in enhancing matrix structure. However, for the 30% replacement level, even though the compressive strength at 90 days is slightly lesser when compared to the 20% replacement level, but still this value is still higher than that of the control mix for 7,14 & 28 days curing periods.

Table 5. Compressive Strength Test Result

SF+SPD (% by weight of Cementitious Material)	Average Compressive strength (MPa)			
	7-days	14-days	28-days	90-days
0	19.48	25.37	42.85	48.31
5	20.69	25.99	43.28	48.53
10	21.17	26.51	43.85	49.28
20	22.41	27.78	45.13	49.79
30	19.72	26.18	41.72	47.62

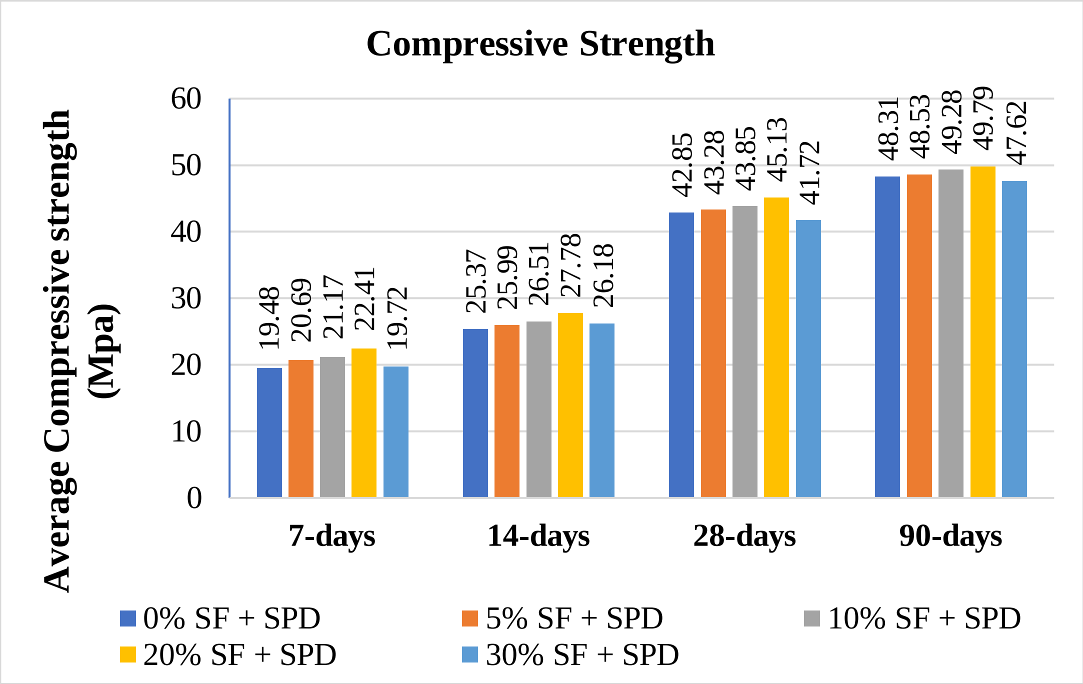


Figure 2 Compressive Strength Test Result

3.2 Split Tensile strength

Table 6 and Figure 3 shows the split tensile strength test result. For the control mix (0% SF + SPD), the 7-day split tensile strength is found to be 2.15 MPa, gradually increasing to 2.64 MPa at 14 days, 3.51 MPa at 28 days, and 3.65 MPa at 90 days indicating a consistent strength development.

For the mix with 5% replacement of SPD and SF, split tensile strength marginally increased to 2.20 MPa at 7 days, 2.72 MPa at 14 days, 3.62 MPa at 28 days, and 3.71 MPa at 90 days. Even with the 10% replacement level,

the strength increased to 2.38 MPa, 2.77 MPa, 3.70 MPa, and 3.74 MPa at 7, 14, 28, and 90 days respectively, indicating that SPD and SF can help increase the tensile strength of SCC.

These test results indicate that 20% replacement results in the highest split tensile strength of 2.43 MPa, 2.85 MPa, 3.78 MPa, and 3.83 MPa at 7, 14, 28, and 90 days, respectively, indicating this replacement level maximizes tensile properties through the enhancement of matrix cohesion and densification. Nevertheless, replacement with 30% resulted in a slight reduction of tensile strength to 3.55 MPa at 90 days.

Table 6. Split Tensile Strength Test Result

SF+SPD (% by weight of Cementitious Material)	Average Split-Tensile strength (MPa)			
	7-days	14-days	28-days	90-days
0	2.15	2.64	3.51	3.65
5	2.20	2.72	3.62	3.71
10	2.38	2.77	3.70	3.74
20	2.43	2.85	3.78	3.83
30	2.09	2.52	3.59	3.55

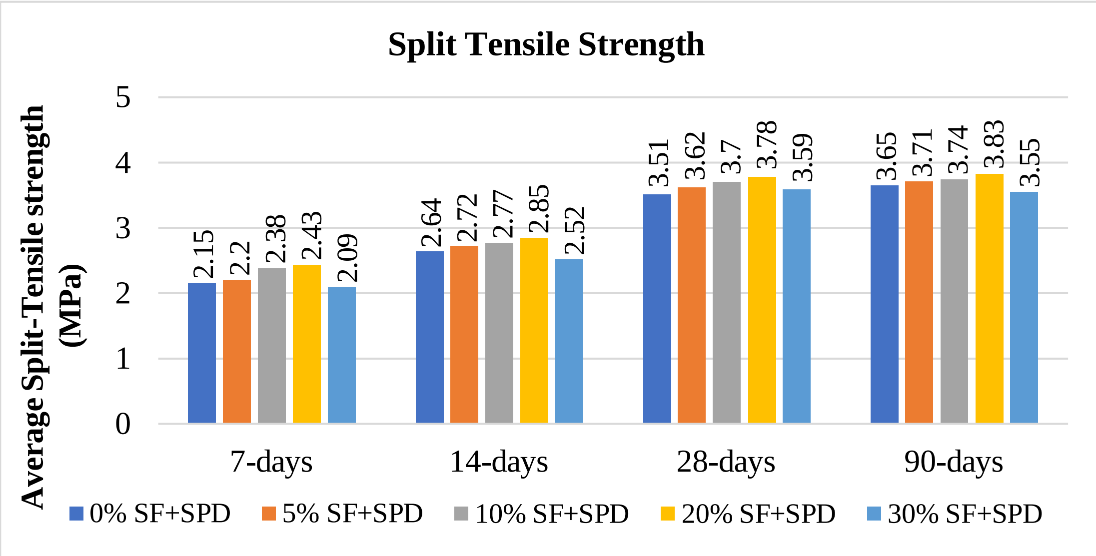


Figure 3. Split Tensile Strength Test Result

3.3 Flexural strength

Table 7 and Figure 4 shows the flexural strength test result. The 7-day flexural strength for the control mix (0% SF + SPD) was 2.65 MPa, and it increased gradually to 3.35 MPa at 14 days, 4.23 MPa at 28 days, and reached

4.60 MPa at 90 days. It demonstrated a steady increase in flexural strength with the curing period.

A marginal improvement in flexural strength was observed with a 5% replacement of SPD and SF, reaching 2.79 MPa, 3.38 MPa, 4.27 MPa, and 4.67 MPa at 7 days, 14 days, 28 days, and 90 days, respectively. This positive trend continued with a 10% replacement level and the flexural strength increasing to 2.87 MPa at 7 days; 3.52 MPa at 14 days; 4.32 MPa at 28 days; and 4.76 MPa at 90 days. This improvement could imply the cumulative effect of SPD and SF contributing to the increase in flexural strength of the SCC mixes.

At the 20% replacement level, the values of flexural strength reached 2.95 MPa, 3.63 MPa, 4.55 MPa, and 4.97 MPa at 7, 14, 28, and 90 days, respectively, resulting in the highest flexural strength. Further testing revealed a likely optimum replacement level, which offers increased particle packing and pozzolanic activity, resulting in improved matrix cohesion and flexural strength.

Flexural strength data showed a small drop (2.63 MPa, 3.30 MPa, 4.25 MPa, and 4.54 MPa at 7, 14, 28, and 90 days, respectively) at the replacement level of 30%. This reduction suggests that beyond 20% replacement, the reduced OPC content may not support the gain in flexural strength.

Table 7. Flexural Strength Test Result

SF+SPD (% by weight of Cementitious Material)	Average Flexural strength (MPa)			
	7-days	**14-days**	**28-days**	**90-days**
0	2.65	3.35	4.23	4.60
5	2.79	3.38	4.27	4.67
10	2.87	3.52	4.32	4.76
20	2.95	3.63	4.55	4.97
30	2.63	3.30	4.25	4.54

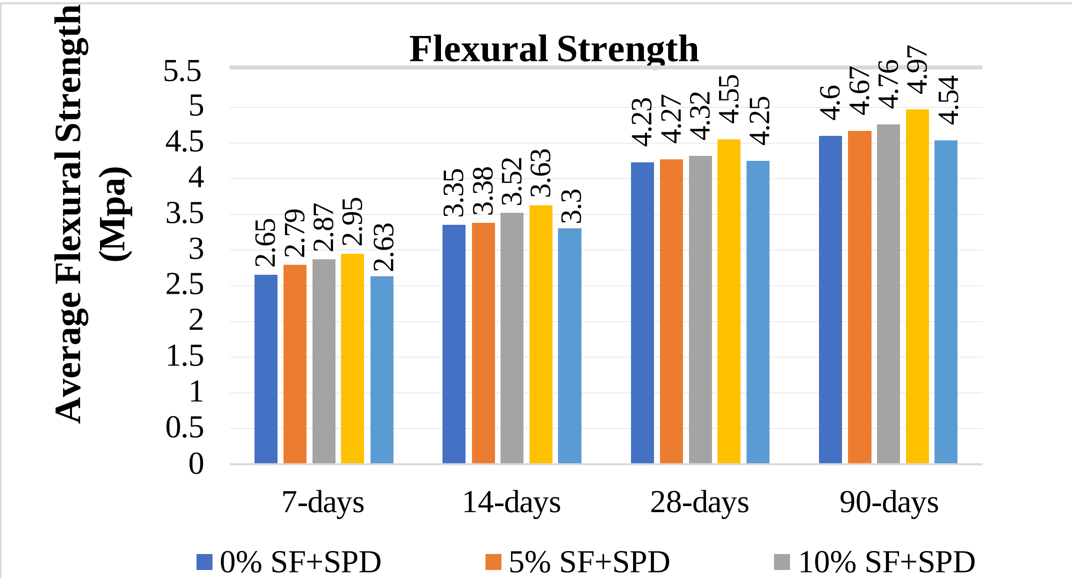


Figure 4 Flexural Strength Test Result

4. Conclusion

Results of this study on the use of stone polishing dust (SPD) and silica fume (SF) as partial replacements for Ordinary Portland Cement (OPC) in self-compacting concrete (SCC) and partial replacement of fine aggregate with granite stone dust (GSD) have revealed valuable information on the mechanical properties of SCC. The conclusions based on compressive, tensile, and flexural strengths tests over curing periods of 7, 14, 28, and 90 days are as follows:

4.1 Compressive Strength

Compressive strength of SCC mixes with partial replacements of OPC using SPD and SF demonstrated significant improvement in strength in comparison to the control mix. The 20% replacement level achieved the highest 90-day compressive strength of 49.79 MPa, likely because of the synergy of SPD and SF in refining the microstructure and improving the matrix density.

Nevertheless, compressive strength reduced slightly at 30% replacement, suggesting that beyond 20%

replacement, the OPC dilution effect may limit its ability to contribute to the compressive strength gain beyond 20% replacement. In general, the addition of SPD and SF showed an increase in compressive strength, particularly at lower replacement levels, suggesting that SPD and SF are promising sustainable materials for contribution to SCC.

4.2 Split Tensile Strength

The test results indicate that the split tensile strength increases with the level of replacement for all levels of replacement with a maximum 90-day tensile strength of 3.83 MPa for 20% SPD and SF mix. At this optimum level replacement, the increased tensile strength suggests that improved matrix cohesion and densification caused by these fine particles in the SPD and SF have improved interface bonding within the concrete itself. At 30% replacement, however, split tensile strength is slightly reduced, which may indicate a structural imbalance in the binder composition disrupting the matrix beyond this level of replacement.

4.3 Flexural Strength

Following a similar trend, maximum flexural strength was achieved by the mix with 20% replacement of 4.97 MPa at 90 days. This replacement level might have resulted in enhanced particle packing combined with pozzolanic reaction which strengthened the resistance of concrete to flexural stresses. At the 30% replacement level, however, a slight decrease in flexural strength is noted and this may be attributed to the reduction in OPC content, which may not sufficiently support future strength gains. A balanced replacement level is necessary to optimize mechanical performance, as indicated by the flexural strength results.

In conclusion, it is observed that 20% by weight of OPC is the optimal replacement level for SPD and SF in SCC in regard to its compressive, tensile and flexural strengths. Thus, this replacement level acts both as an effective pozzolanic replacement and as a filler, and it improves the matrix microstructure and strengthens the mechanical properties of SCC. SPD and SF are viable partial replacements for OPC, which exhibit performance improvements relative to the control mix, even at lower replacement levels (5 and 10 percent), which in turn show reduced strength gains compared to higher replacement level (30 percent). Further, the inclusion of GSD as partial replacement of fine aggregate positively contributed to the strength aspects, notably in flexural and tensile strengths, which supports the material potential in the sustainable concrete production.

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