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# Assessment of the compressive strength of recycled waste LCD glass concrete using the ultrasonic pulse velocity

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## HIGHLIGHTS

- A UPV-based compressive strength prediction model of waste LCD glass concrete is proposed.
- The relationship between compressive strength and UPV present a nonlinearly increasing curve.
- The strength-UPV curve has a right shift tendency as the glass replacement increases.
- The UPV increases with the waste glass replacement G value, but the compressive strength decreases as the G value increases.

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## ABSTRACT

This study uses a fixed weight ratio of 7:2:1 of cement, fly ash and slag powder as binder material and uses waste liquid crystal display (LCD) glass sand through a No. 4 sieve to replace 0%, 10%, 20% and 30% of the fine aggregate using the volumetric method, combined with water-binder ratios (w/b) of 0.28, 0.32 and 0.36 for a series of tests to determine the compressive strength and ultrasonic pulse velocity (UPV) of self-consolidating glass concrete (SCGC). The test results show that the compressive strength and UPV increase with age but decrease as the water-binder ratio increases. The compressive strength and UPV present a nonlinearly increasing relation curve, the water-binder ratio influences the curve insignificantly, and there is a right shift as the waste glass replacement increases. Therefore, the UPV of SCGC increases with the waste glass replacement G value, but the compressive strength decreases as the G value increases. In addition, this study uses the exponential function as a basis, combined with the compressive strength and UPV characteristics of waste LCD glass concrete; by considering the w/b, waste glass replacement G and UPV variables, the compressive strength prediction model is deduced. The analysis results show that the mean absolute percentage error (MAPE) value for the compressive strength test result and the assay value of SCGC is 6.45–7.97%; compared with the MAPE value, which is 8.61–12.51%, as obtained by linear function regression, the analysis result accuracy is increased by 25.1–36.3%. In the same way, the MAPE value of the WGCLSM (waste glass controlled low strength material) is 8.15–11.24%; compared with the MAPE value, which is 21.33–26.19%, as obtained by linear function regression, the accuracy is increased by 51.2–62.2%. Furthermore, the MAPE value obtained by a compressive strength prediction analysis of HPGC (high-performance recycled liquid crystal glass concrete) is 7.18–8.65%. Therefore, this study builds an analytical model that uses UPV to evaluate the compressive strength; its forecast accuracy is good, and it is applicable to waste LCD glass concrete for different functional requirements. It is very helpful for the safety assessment analysis of concrete structures with similar mix proportions and nondestructive testing UPV.



## 1. Introduction

Taiwan's flat-panel display industry has flourished over the past decade. Taiwan's output accounted for 38% of the global large-size LCD (liquid crystal display) panel production in 2011, and it has become one of the largest producers of LCD panels, second only to Korea. Large amounts of waste are derived from the manufacturing process with the substantial increase in production [1]. The output of waste LCD glass in Taiwan reached 20,000 tons in 2007 [2]. Waste glass recycling can reduce the material cost and demand for valuable landfill space, thereby decreasing both the effect on

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the environment and $CO_2$ emission, which are the preferred outcomes for sustainable environmental protection. Recycled glass has been used and applied in asphalt concrete, normal concrete, back-filling, sub-base, tiles, masonry blocks, paving blocks and other decorative purposes [3]. Adding crushed waste glass to concrete as a fine aggregate can reduce the concrete air content and unit weight, more efficiently pack the concrete pores, and provide better durability, surface resistance, resistance to acid, salt and alkali [4–6]. Hence, waste glass has been widely used to replace some of the concrete or cement mortar material [4–14].

The compressive strength of concrete is an excellent indicator of concrete quality, and it invariably forms the most important basis of specifications and quality control [15]. In addition, in designs, concrete is mostly used under compression loading; therefore, concrete is directly related to the compressive strength from a design perspective [16]. Thus, for the safety assessment of existing structures, compressive strength is an important indicator. In engineering practice, the in situ compressive strength can be obtained by coring samples, and it is often suggested when no more strength information can be referenced. However, coring is a destructive technique and may have some limitations in structures. Ultrasonic pulse velocity (UPV) is a non-destructive technique that involves measuring the speed of a wave through material to predict its strength, calculate the low-strain elastic modulus or detect the presence of internal flaws, such as cracking, voids, honeycomb, decay and other damage. This technique is applicable where intrusive (destructive) testing is not desirable, and it can be applied to concrete, ceramics, stone and timber. UPV values are affected by a number of factors, including the mix proportions, aggregate type, age of concrete, and moisture content. However, the factors that might significantly affect the strength of the concrete have little influence on the UPV [17–19]. If the relationship between the compressive strength and UPV could be established, it would be very helpful for the safety assessment and analysis of structures during its service period. In this study, a series of compressive strength and UPV tests were carried out with a varied water-binder ratio on the self-consolidating glass concrete (SCGC), and an assessment of the compressive strength using UPV was proposed.

## 2. Experimental plan

### 2.1. Test materials

1. Cement: Type I Portland cement produced by the Taiwan Cement Corporation was used; its properties conformed to the Type I Portland cement specified in ASTM C150.
2. Mixing water: Conforms to ASTM C94 concrete mixing water.
3. Aggregate: The aggregate originated from the Ligang District and conformed to ASTM C33.
4. Fly ash: Class F fly ash from the Taiwan Taipower Xing-Da Thermal Power Plant conformed to ASTM C618.
5. Slag: GGBFS (ground-granulated blast-furnace slag) was produced by the CHC Resources Corporation and was ground into 4000 $cm^2/g$, and its properties conformed to ASTM C989.
6. Glass sand: TFT-LCD (thin film transistor-liquid crystal display) waste LCD glass sand able to pass through a No. 4 sieve was provided by Chi-Mei Optoelectronics. The glass sand had a smooth surface with edges and corners, and the fineness modulus and SSD (saturated-surface-dry) specific weight were 3.37 and 2.45, respectively. The particle size distribution curve was also close to the natural sand of the Ligang District.
7. Superplasticizer: A Type 1000 superplasticizer that complied with the ASTM C494 type G admixture.

### 2.2. Test variables and method

The volumetric method was used for the proportion design of the mixture. In this study, the fly ash and slag powder were added and mixed with cement as binder material. The ratio of cement-fly ash-slag was 7:2:1 by weight. The water-binder ratios were 0.28, 0.32, and 0.36, and four types of glass sand as fine aggregate were added at volume replacement ratios of 0%, 10%, 20%, and 30%. A 10 cm * 20 cm cylindrical concrete specimen was made and solidified. The specimens were placed and cured at room temperature (23–25 °C) and in saturated limewater. The compressive strength and UPV were tested at the ages of 1, 7, 28, 56, 90, and 180 days in accordance with ASTM C31, ASTM C39, and ASTM C597.

The physical properties of the aggregate and glass sand are shown in Table 1. The unit weight of the mix design SCGC materials are shown in Table 2. The chemical properties of the cement, fly ash, slag, and glass sand and the particle size distribution curves of aggregate and glass sand can be found in our previous study [20,21].

## 3. Experimental results

### 3.1. Effect of water-binder ratio on compressive strength and UPV

Figs. 1 and 2 show the test results of the relationships of the compressive strength and UPV to the age of the SCGC with different w/b ratios and waste glass replacements (G). It is observed that within a curing age of 180 days, the compressive strength and UPV increase with age but decrease as w/b increases, consistent with the findings of other studies [22,23]. Disregarding the effect of waste glass replacement, the average gradient of the decrease of the compressive strength at the age of 28 days with w/b is approximately −210 MPa, and the decreasing gradient at an age of 90 days is approximately −160 MPa, as shown in Fig. 3(a). Therefore, the effect of w/b on the short age strength is slightly greater than that on the long age strength. In the same way, disregarding the effect of waste glass replacement, the average gradient of the decrease of the UPV at an age of 28 days with w/b is approximately −620 m/s, and the decreasing gradient at an age of 90 days is approximately −720 m/s, as shown in Fig. 3(b). However, the effect of w/b on the short-age UPV is slightly less than that on the long-age UPV.

In terms of the concrete material, the UPV is likely to be influenced by age, w/b, cement content, water and aggregate property; thus, the pulse velocity and transmission path will be different. Generally speaking, coarse aggregate has a higher pulse velocity than fine aggregate does, and fine aggregate has a higher pulse velocity than cement mortar does. Therefore, the more coarse aggregate the concrete contains, the higher the pulse velocity is in the same unit volume. The pulse velocity decreases as the water consumption and gaps increase. Therefore, the relationship between the compressive strength and UPV is closely related to the concrete mix. Breysse [24] further condensed the UPV strength and rebound number strength models by utilizing three commonly

**Table 1**
Physical properties of aggregate and glass sand.

| Properties | Coarse aggregate | Fine aggregate | Glass sand |
|---|---|---|---|
| Unit weight ($kg/m^3$) | 1530 | 1820 | 1680 |
| Particle density ($g/cm^3$) | 2.62 | 2.57 | 2.45 |
| $D_{max}$ (mm) | 9.50 | 1.18 | 2.36 |
| Water absorption (%) | 0.7 | 1.2 | 0.4 |
| Fineness modulus (FM) | 5.02 | 3.22 | 3.37 |
| Soil content (%) | 0.5 | 1.3 | – |